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DECISION SIGHT DISTANCE FOR HIGHWAY DESIGN AND TRAFFIC CONTROL REQUIREMENTS

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Offices of Research & Development

Washington, D. C. 20590

FOREWORD

This report summarizes the results of a synopsis and field validation of the decision sight distance concept as it relates to highway design and traffic operations. The report will be of interest to traffic and highway design engineers concerned with the hazard avoidance process.

The report presents current sight distance guidelines, dicusses the decision sight distance concept, recommends and evaluates through field studies specific values, and recommends applications for the use of decision sight distance values.

Sufficient copies of this report are being distributed to provide a minimum of one copy to each FHWA Regional Office, one copy to each FHWA Division Office and three copies to each State highway agency. Direct distribution is being made to the Division Offices.

D. Solomon

for Charles F. Scheffey
Director, Office of Research
Federal Highway Administration

NOTICE

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16. Abstract

Decision sight distance (DSD) has been defined as the distance at which drivers can detect a hazard or signal in a cluttered roadway environment, recognize it or it's threat potential, select the appropriate speed and path, and perform the required action safely and efficiently. A research effort was devised and performed to relate this concept to specific road types, design speeds, traffic operating conditions, geometric features, and driver attributes. It was performed in two phases, with the following objectives:

Phase I: Critically evaluate and synthesize relevant literature pertaining to DSD and derive values for highway design. Phase I led to the identification of a hazard avoidance process model as a basis for quantifying decision sight distance. The process includes three elements of information processing-detection, recognition and decision-making followed by initial response and vehicle maneuver. The outcome of Phase I was the development of preliminary DSD values based on the estimated times for the various elements of the model as reported in the literature.

Phase II: Validate, via highway field study, derived DSD values. In Phase II, 19 subjects drove an instrumented vehicle through eight typical highway situations in order to validate the preliminary values. In general, the results of the field study supported the derived DSD values, with some modifications, and confirmed that decision sight distance is operationally valid. Recommendations are presented on the decision sight distance criteria, and its application for design and traffic operations.

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I. INTRODUCTION

Background

A primary feature in the design of a highway is the arrangement of the geometric elements so that there is adequate sight distance for safe and efficient operation (1).* With this principle in mind, the American Association of State Highway and Transportation Officials (AASHTO) has established guidelines for three important sight distance considerations: (a) safe stopping sight distances (minimum and desirable), which provides for detecting an obstacle and bringing the vehicle to a stop, (b) passing sight distance, which provides for initiation and completion of a passing maneuver, and (c) intersection sight distance, which provides visibility for vehicles crossing or entering an intersection. These distances, however, are often inadequate for situations with high decision complexity, when the development of a potentially hazardous situation is difficult to perceive, and when severe braking is inappropriate. At locations where longer distances are needed, a review of human factors and traffic operations considerations shows that sight distance criteria should be based on the driver's ability to properly react to impending danger. This concept has been referred to as decision sight distance.

Decision sight distance has been defined as the distance at which drivers can detect a hazard or signal in a cluttered roadway environment, recognize it or its threat potential, select the appropriate speed and path, and perform the required action safely and efficiently (2). The concept of decision sight distance thus incorporates a number of factors not taken into account by stopping sight distance. Appropriate application of the concept should afford a driver sufficient distance to maneuver his vehicle with a reasonable margin for error.

While decision sight distance has been conceptually defined, little attempt has been made to relate decision sight distance to specific road types, design speeds, traffic operating conditions, geometric features, and driver attributes. Considerable relevant data exist, however, on aspects of this problem. For example, data have defined scanning characteristics (3); rear and side view mirror dwell time (4, 5); aspects of signal detection in clutter (6); and complex reaction time (7, 8).

Several attempts have been made to develop recommended values of sight distance relative to design speed (9, 10). These values, called "anticipatory sight distance," were based on motion perception of drivers and do not account for clutter, decision complexity, and required vehicle maneuvers. Others have tried to relate sight distance to the density of events occurring in various roadway environments (11) or to driver's workloads (12). Finally, numerical values have been established empirically for the special case of two-lane passing sight distance (13).

*Numbers in parenthesis refer to references.

Research is, therefore, needed to (a) bring together applicable knowledge pertaining to decision sight distance and (b) develop a means for applying this concept to highway design and traffic control requirements.

Objectives

This two phase study had the following objectives: (a) to critically evaluate the state-of-the-art of knowledge pertaining to decision sight distance and related factors; and (b) to evaluate, under highway operating conditions, proposed decision sight distance values and to recommend operationally valid decision sight distances. The second phase evaluation, was to be a field study in a real-life operational setting for the purpose of "validating" the criteria developed in Phase 1. The information thus gained was then synthesized with applicable design and traffic engineering factors to achieve the following specific objectives:

1. Critically assess pertinent literature bearing on the quantification of decision sight distance.
2. Quantify decision sight distance values appropriate for use by state and local highway agencies in evaluating highway designs and traffic control techniques.
3. Perform a field validation study of the derived decision sight distance values.
4. Develop recommendations for additional research efforts to fill critical gaps in the knowledge of drivers' sight distance requirements.

Essentially, then, the decision sight distance values obtained were to be used for geometric design of highways (as recommended in the AASHTO design policies), as design guidelines for traffic control, and operationally for positive guidance by drivers traveling through hazardous zones (14).

Scope

The two-phase effort described above consisted of a rigorous search through existing literature to develop a table of values for decision sight distance. This was followed by a field study validating the table. Since time and resources were limited, the field study was constrained to a small sample of drivers through a test route to provide an initial data base of responses relative to the derived values.

II. CURRENT SIGHT DISTANCE GUIDELINES

There are three sight distance requirements as established by AASHTO in three AASHTO Policy publications:

- A Policy on Geometric Design of Rural Highways – 1965 ("Blue Book")
- A Policy on Design of Urban Highways and Arterial Streets – 1973 ("Red Book")
- A Policy on Design Standards for Stopping Sight Distances – 1971.

Stopping Sight Distance

Stopping sight distance is based on the concept that the minimum sight distance available on a highway should be sufficiently long to enable a vehicle traveling at or near the design speed to stop before reaching an object in its path. As such, the minimum stopping sight distance is the sum of two distances: the distance traveled from the instant the driver sights an object for which the stop is necessary to the instant the brakes are applied, and the distance required to stop the vehicle after brake application begins. These two components have been commonly labeled as the perception-reaction time and the braking distance.

The present AASHTO guidelines have adopted a uniform value of 2.5 seconds for the perception-reaction time, 1.5 seconds for perception and 1.0 second for brake application. While it was recognized that these values, albeit conservative and accommodating for 85 percent of the driving population, may in fact vary over speed and with different environmental conditions, there was no empirical field research that could substantiate different values.

Table 1 shows the AASHTO minimum and desirable stopping sight distances. The minimums are to be used as such, while the desirable values are to be applied wherever conditions permit. (The desirable values were based on wet pavement conditions.) Sight distances are to be measured from the driver's eye, assumed to be 3.75 feet (1.14 m) above the pavement, to the top of an object six inches (0.15 m) high on the pavement. It is believed that the distances are suitable for trucks, because the greater driver eye height compensates for the longer stopping distances.

Passing Sight Distance

The second sight distance requirement is for passing on a two-lane highway. Passing sight distance for use in design is determined on the basis of the length needed for a single vehicle to safely pass another single vehicle. The minimum passing sight distance for two-lane highways is determined as the sum of four distances:

d_1 – Distance traveled during perception and reaction time and during the initial acceleration to the point of encroachment on the left lane.

Table 1

Minimum and Desirable Stopping Sight Distances (Wet Pavements)

Design Speed	Assumed Speed for Condition		Brake Reaction			Coefficient of Friction	Braking Distance on Level		Stopping Sight Distance			
			Time	Distance					Computed		Rounded for Design	
mph	mph		sec.	feet		f	feet		feet		feet	
	min	des		min	des		min	des	min	des	min	des
30	28	30	2.5	103	110	0.35	75	86	178	196	200	200
40	36	40	2.5	132	147	0.32	135	167	267	314	275	325
50	44	50	2.5	161	183	0.30	215	278	376	461	375	475
60	52	60	2.5	191	220	0.29	311	414	502	634	525	650
65	55	65	2.5	202	238	0.29	348	486	550	724	550	725
70	58	70	2.5	213	257	0.28	400	583	613	840	625	850
75	61	75	2.5	224	275	0.28	443	670	667	945	675	950
80	64	80	2.5	235	293	0.27	506	790	741	1083	750	1100

1 mph = 1.609 km/h
1 ft = 0.3048 m

$K\text{-}SSD = 2.5\left(\frac{88V}{60}\right) + \left(\frac{V^2}{30f}\right)$, where; SSD is Stopping Sight Distance, V is speed in mph, and f is coefficient of function.

d_2 – Distance traveled while the passing vehicle occupies the left lane.

d_3 – Distance between the passing vehicle at the end of its maneuver and the opposing vehicle, which was found to vary from 110 to 300 feet (33 to 90 m).

d_4 – Distance traveled by an opposing vehicle for two-thirds of the time the passing vehicle occupies the left lane, or 2/3 of d_2 above.

Table 2 shows the AASHTO minimum passing sight distances for design of two-lane highways as computed from the summation of the four maneuver distances. As with stopping sight distance, the distance is measured from the driver's eye, 3.75 feet (1.14 m) above the pavement. However, in this case the height of the object (assumed to be a car) is 4.5 feet (1.37 m) from the pavement.

Table 2

Minimum Passing Sight Distance for Design of 2-Lane Highways

Design Speed (mph)	Assumed Speeds		Minimum Passing Sight Distance, feet	
	Passed Vehicle (mph)	Passing Vehicle (mph)		Rounded
30	26	36	1090	1100
40	34	44	1480	1500
50	41	51	1840	1800
60	47	57	2140	2100
65	50	60	2310	2300
70	54	64	2490	2500
75*	56	66	2600	2600
80*	59	69	2740	2700

*Design speeds of 75 and 80 mph are applicable only to highways with full control of access or where such control is planned in the future. NOTE: 1 mph = 1.609 km/h.

Intersection Sight Distance

Finally, the third sight distance requirement established by AASHTO is for at-grade intersections. These distances are for visibility of the intersection and a length of the intersecting highway. Three general cases are considered:

- Case 1 – enabling vehicles to adjust speed at intersections with no stop or signal control
- Case 2 – enabling vehicles to stop at non-controlled intersections
- Case 3 – enabling stopped vehicles to cross a major highway at stop controlled intersections

For Case 1, a sight triangle is established which is defined by the distances traveled by a vehicle in 3 seconds: 2 seconds for perception of and reaction to an approaching vehicle in the adjacent roadway and 1 second to actuate braking or accelerating to regulate speed. The distances so determined are less than stopping sight distance, and are not considered a desirable practice for design.

For Case 2, the sight triangle is defined by the same minimum stopping sight distances for each leg as discussed previously in Case 1.

For Case 3, the sight distance applies to the vehicle stopped at the intersection for visibility of approaching vehicles on both adjacent legs. A value of 2 seconds for the perception-reaction time was assumed by AASHTO in developing the sight distance equation.

III. CONCEPT OF DECISION SIGHT DISTANCE

Definition

An approach to quantifying decision sight distance is to base it on its definition. Decision sight distance has been defined as:

> "The distance at which a driver can detect a signal (hazard) in an environment of visual noise or clutter, recognize it (or its threat potential), select appropriate speed and path, and perform the required action safely and efficiently."(2)

Within this definition there are several key phrases to consider, and these are discussed below.

Distance at Which a Driver Can Detect . . .

By detection is meant the process of seeing the hazard (assuming the sensory input is visual rather than tactile or auditory), although not necessarily recognizing or perceiving it as such. It is the first step or event in information processing, and as such is concerned with the ability of the driver to see.

Detection is dependent upon the interaction of several factors associated with the hazard, the driver, and the environment, including

- visibility of the hazard
- conspicuity of the hazard
- number of information sources competing for a driver's attention
- scanning behavior
- static and dynamic visual acuity
- prior knowledge
- expectancy
- vigilance.

It should also be noted that both static and dynamic visual acuity (the resolving power of the eye when there is relative motion between observer and object) is influenced by vehicle factors such as windshield condition, but primarily by driver factors such as

- age
- health
- color vision
- condition of central nervous system affected by drugs, alcohol, carbon monoxide, fatigue, etc.
- glare recovery.

With so many factors affecting visual acuity, the moment of detection can vary considerably. Detectability is a key element in decision sight distance, since hazards themselves can be made more visible, the visibility period (distance) can be extended, or warning devices can be provided to alert the motorist of the impending hazard.

Signal (Hazard) in an Environment of Visual Noise or Clutter

In this definition, the term "signal" is used, not necessarily to indicate a traffic signal (although it could be that), but rather any stimulus which requires a driver's attention. More importantly, it refers to a "hazard" and here again, this term is interpreted in its broadest sense to mean not only an object in a driver's path, but also any situation requiring a transition or change in path and/or speed.

Roadway hazards can be classified into three general types (2):

1) Object hazard – fixed or moving;

2) Highway condition hazard – a geometric condition or the condition of the road itself;

3) Situation hazard – combination of conditions with or without an object hazard.

Further discussion of these hazard types is in order for the purpose of identifying those hazards for which decision sight distance should apply. It should be noted that decision sight distance is intended to be applied in two ways. The first is in highway design, either for new facilities or reconstruction (improvement) of "below standard" facilities. It also is applicable in the identification of traffic control techniques, especially for hazardous locations. In this latter application, decision sight distance is used in the Positive Guidance process to define zones (advance, approach, and non-recovery) for information presentation (14). These two applications, highway design and traffic control, will have a bearing on the type of hazard to be considered for decision sight distance.

Object Hazards. The first type of hazard to consider is the object hazard which can be either fixed or moving. Fixed objects are roadway furniture items, such as sign supports, guardrails, bridge rails, etc., or natural features such as trees, embankments, etc., which are not normally found within the traveled way but which often result in serious accidents when hit. Since current design standards require that these potential hazards be placed far from the edge of the roadway, decision sight distance of these hazards is not always required for design purposes. However, for existing substandard facilities, decision sight distance criteria are applicable when a fixed object is close enough to the roadway to require an avoidance maneuver.

Moving object hazards consist of anything that moves into a driver's path. Included would be vehicles, trains, pedestrians, and animals. Based on the definition of decision sight distance, this type of hazard is generally not of concern. Pedestrians and animals can appear in the driver's path at any time; for this occurrance stopping sight distance criteria apply. While the train is indeed a hazard, it is the at-grade crossing (more correctly defined as a highway condition hazard) which requires proper sight distance. Finally, vehicles, like pedestrians and animals, can move into a driver's path at any time and, therefore, stopping sight distance should apply here as well. (One obvious exception is for the situation of passing on a two-lane highway, where there is the possibility of an opposing vehicle.) However, the presence of vehicles can add to hazardousness by making it more difficult to detect and respond safely to the primary hazard. For example, drivers positioned in a lane which is to be dropped might find the lane drop more difficult to perceive and react to if the traffic volume were heavy than if no vehicles blocked their line of sight.

Condition Hazards. A second major type of hazard is categorized as a highway conditions hazard, which can be either a design feature or a road condition. The latter includes sections of the road with poor superelevation, pot holes, etc. Decision sight distance would apply to conditions such as poor superelevation or slippery pavement surfaces, but not to any temporal conditions such as pot holes, whose locations cannot be predetermined. Certain design features are the most important type of hazard where the decision sight distance concept applies. There are numerous design features which generally require a driver to depart from the simple steering and speed control maneuvers performed to follow the road. Such locations are where most drivers experience information handling problems. They encompass all interchanges and intersections, railroad-highway grade crossings, driveways, areas with changes in cross section (e.g., pavement width transitions, narrow bridges), toll plazas, lane drops, and any locations where unusual or unexpected maneuvers are required (e.g., isolated curve sections, detours, construction areas).

Situation Hazards. Situation hazards arise when there is a combination of conditions with or without object hazards. This type of hazard is best described by way of an example – a horizontal curve with insufficient superelevation and polished surface combined with a vehicle with bald tires during rain. This combination of individual hazards leads to a potentially dangerous situation. This type of hazard, while often fixed in location depending on the situation, is temporal in nature. Decision sight distance would apply for this type of hazard only for traffic control requirements. A case in point is that it would be necessary to provide a warning sign in advance of a bridge which is subject to differential icing.

Inefficient system operations (indicated by delays, long queues, or congestion) usually represent a non-catastrophic system failure, but sometimes lead to situations with more serious consequences. In this context, inefficient systems operations are treated as a fourth class of hazard (14). In this case, the hazard could be the end of a queue "just around the curve." While the location of the hazard is rarely fixed, decision sight distance criteria could be applicable for locating such traffic control devices as real-time warning signs.

While the decision making process is often complex for the driving task, the identification of an object hazard is usually simple and error-free. However, the perception of highway condition and situation type hazards may be neither simple nor error-free, particularly when the hazard is in an environment of visual noise or clutter.

Visual noise or clutter is defined as a situation where there are multiple stimuli, often irrelevant to the driving task, in close proximity. In terms of the highway situation, it implies that along a section of road there may be a number of traffic control devices with different items of information competing with peripheral attention-getters as advertising signs, trees, etc. A busy urban street would be an extreme example of an environment of visual noise. In such a complex environment, it is more difficult for the driver to detect and respond to a hazard.

Recognize It (or Its Threat Potential)

The next step in information processing is signal recognition or perception, which is defined as the process of selecting information detected by the senses and their transformation into useful form for analysis and interpretation. This is when the brain translates the image "detected" by the eye into a recognizable object. This step follows detection in time. Up to and through this process, there is usually no motor response.

Recognition of one of the previously described hazards depends upon the driver and the hazard. A primary factor that comes into play is a driver's prior knowledge from experience and training (long-term) or from recent experience with similar hazards while driving on the highway (short-term).

Select Appropriate Speed and Path

The selection of the appropriate speed and path involves decision making. When drivers find themselves on a collision course with another vehicle or an object, the reaction (severe braking and/or swerving) is almost instantaneous after perception.

But given the opportunity to take some other, less drastic corrective action, there will be a period of decision making, which is described as a three-part process involving

1. Identification of alternative courses of action,
2. Evaluation of the probability of success of each alternative, and,
3. Selection of the appropriate course of action (speed and path) (2).

This decision process starts immediately after recognition (or perception) of the hazard and stops when there is limb movement, e.g., when the foot is taken off of the accelerator or steering wheel movement is initiated. It has been described as the throughput phase, when the hazard is diagnosed as to its severity, alternative evasive actions are considered, and a final action is selected (15). In a sense, it can be labeled as the information processing phase. It is explained here in a simple sequential fashion where, in all likelihood, the motorist may take some intervening actions while he continues to weigh alternative courses of action.

The decision making capability of drivers is affected by several factors including:

- Experience and training – the more experience and training one has, the more quickly one can arrive at a suitable decision.
- Memory – both long and short term memory come into play. A motorist who drives the same road every day builds up a long term memory which can be brought to bear in the decision-making process. Also, a driver acquires a short-term memory bank based on his exposure to similar hazards.
- Emotions – the driver's emotional state as well as the effects of fatigue, drugs, illness, etc. can reduce his ability to make quick and proper decisions.
- Number of alternatives – past research has shown that information is quantified in "bits" (one bit being defined as the amount of information which reduces uncertainty by half.) As the information (or alternatives) increase in number or complexity, the amount of time required to reach a decision also increases.

Perform the Required Action Safely and Efficiently

Having selected the appropriate action, the final step is to initiate and complete the maneuver. In some cases, the maneuver will be a lane change (e.g., for lane drops, pavement width transitions, exit and entrance ramps), for others, it may be a speed change (toll plaza, horizontal curve, etc.) or possibly both. In the case of the lane change, the maneuver cannot always be initiated immediately after the decision process. Gaps in the vehicle stream (left, right, or both) must also be detected, recognized, and assessed as to their acceptibility. Since in the face of an impending hazard there is a sense of urgency to change lanes, drivers may accept relatively short gaps. However, the decision sight distance should provide sufficient length to accommodate a "safe and efficient" merge when necessary.

Once the decision is made to change speed by either decelerating or accelerating, the action can be initiated immediately in most cases. The normal situation would be to reduce speed at a comfortable deceleration rate (about 9 feet per second per second [2.7 m/s^2]) to a speed considered safe to negotiate the hazard or possibly come to a gradual stop (e.g., for a toll plaza).

Hazard Avoidance Model for Decision Sight Distance

Having defined decision sight distance and its components, the next step is to formulate a model for quantifying appropriate distances. Based on the previous discussion, it can be said that there is a sequential chain of events which occurs in hazard avoidance starting from detection of the hazard and ending with completion of the avoidance maneuver. Figure 1 illustrates this chain of events or process using the lane drop exit as an example of a condition-type hazard. This process was adopted and modified from one originally developed by Baker and Stebbins (16) which was later modified by Leisch (9) and Pfefer (10).

The process is briefly described as follows:

- *Hazard becomes visible* (time t_0) – This is the base line time point when the hazard is within the driver's sight line.
- *Hazard is detected* (time t_1) – Driver's eye fixates on the hazard and "sees" it.
- *Hazard is recognized* (time t_2) – The image on the eye is translated by the brain and the hazard is recognized or perceived as such.
- *Driver decides on action* (time t_3) – Driver analyzes alternative courses of action and selects one.
- *Driver begins response* (time t_4) – Driver initiates required action.
- *Maneuver is completed* (time t_5) – Driver changes path and/or speed of vehicle to new state.

The process as described above is a simple additive model, with the total time from the moment when the hazard is visible to the completion of hazard avoidance maneuver equaling the sum of the incremental times for detection (t_0-t_1), recognition (t_1-t_2), decision (t_2-t_3), response (t_3-t_4), and vehicle maneuver (t_4-t_5). Also identified in Figure 1 is the reaction time, which here is defined as all activities up to the vehicle maneuver.

Synthesis of Findings Related to Decision Sight Distance

Decision sight distance has been conceptualized as an additive model which can now be used to formulate appropriate values. Data for quantifying the various components of the model were gleaned from the existing literature. This section presents findings from previous research dealing with the total hazard avoidance process from detection of the hazard through the avoidance maneuver. It is structured after each of the five components of the additive model.

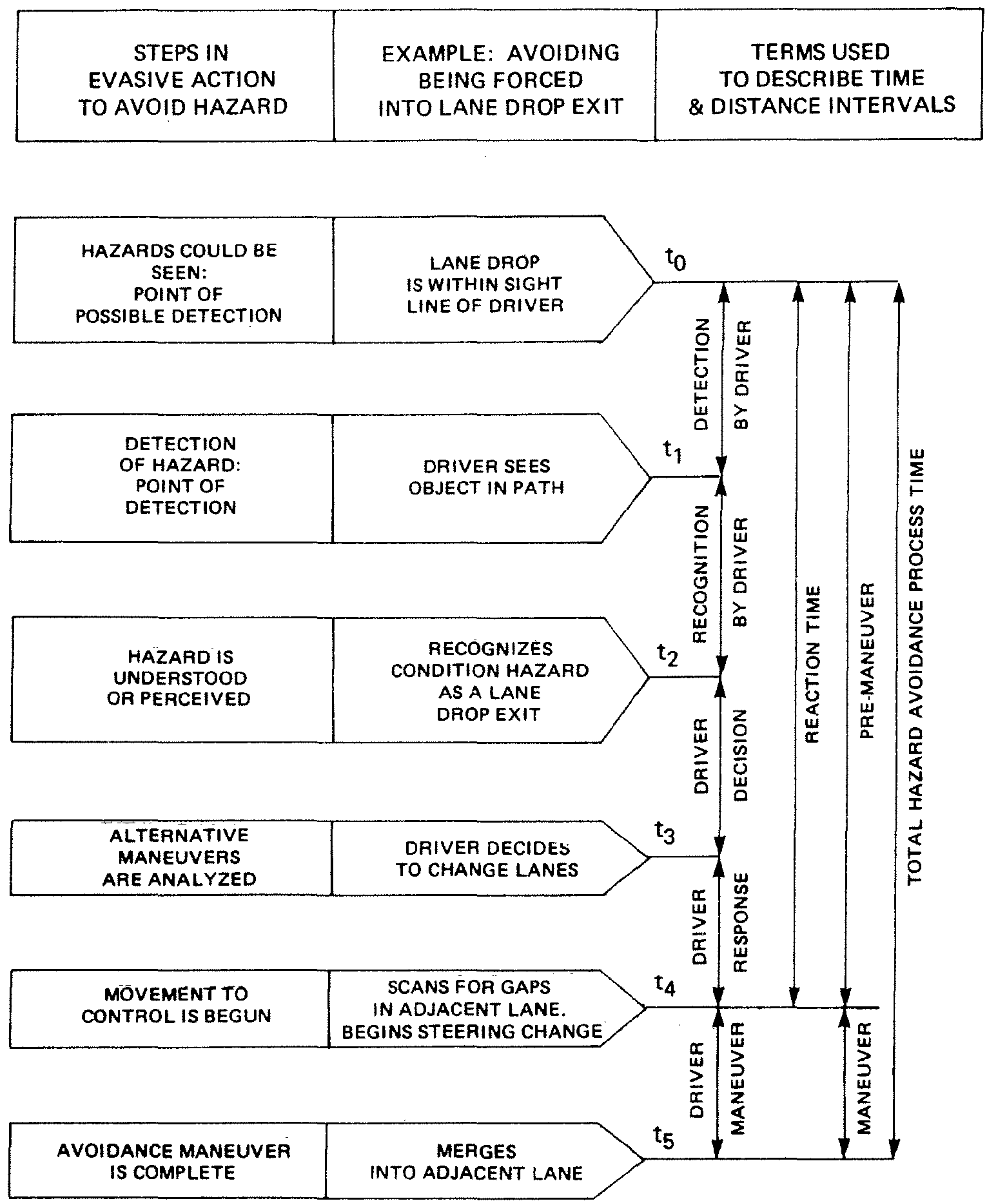


Figure 1. The Hazard Avoidance Process

Detection Time

In the context of the additive model shown in Figure 1, detection time is the period from onset of the hazard (stimulus) to the moment when the image of the hazard is registered on the brain. "Onset of the hazard" means that it is within the driver's cone of vision and there is nothing obstructing its visibility other than the possible inattentiveness and the acuity capability of the driver.

The detection process ends when the image is registered on the brain. Many objects are 'seen" by the eye but not registered on the brain. This is an important distinction representing the filtering process, when some objects are seen but not registered while others are seen depending upon the importance of the object (concept of primacy – refers to the relative importance of information needed by or presented to the driver).

The time required for detection of an information source or hazard is composed of latency, eye movement, and fixation times. Latency is defined as the delay between the time the stimulus is presented and the time the eyes begin to move. Typically this time period could be 0.2 seconds (17) or even longer if the driver's vigilance is low due to fatigue, lack of events, general inattentiveness, etc.

Eye movement to the hazard will in most cases be required, especially if the hazard is in the driver's peripheral vision. Eye movement times have been found to vary between 0.029 and 0.10 seconds for movements of 5 to 10 degrees, respectively (12).

After eye movement to bring the object into the cone of foveal or central vision, the eye must fixate it to be seen. Mourant et al. (3) reported mean fixation times of 0.28 seconds for observing road and lane markers. For hazards it is likely that fixation times would be longer.

Assuming that detection requires all of the mean fixation time (0.28 seconds), possible eye movement (0.029 to 0.10 seconds) and latency (0.2 seconds), the total detection time could range from 0.51 to 0.58 seconds or even longer.

Slightly higher times for the detection process are presented by Mullin (18) who claims that it takes 0.1 to 0.3 seconds to fixate and another 0.5 seconds to perceive an object in an urban situation. (Mullin's perception, as he describes it, more appropriately falls into the detection sequence. He also reports yet another second for accommodation or focusing on the object which implies recognition or perception time.)

Recognition Time

In the hazard avoidance process model, recognition is used interchangeably with perception. It implies a period of time for the brain to interpret the image the eye has focused on as a hazard and to assign it a certain primacy. In the example shown in Figure 1, the driver will have both "seen" and recognized the lane drop exit as a potential hazard by the end of the recognition phase.

While it is acknowledged in the literature that there is a period of time for the recognition process, few researchers have provided data to quantify it. As noted above, Mullin (18) claims as much as one second is required to focus and accommodate (which implies a recognition process) an object sighted in an urban situation.

Glennon (19) notes that perception time may be less at higher speeds because drivers are usually more alert. However, it is known that there is a degradation in visual acuity at higher speeds.

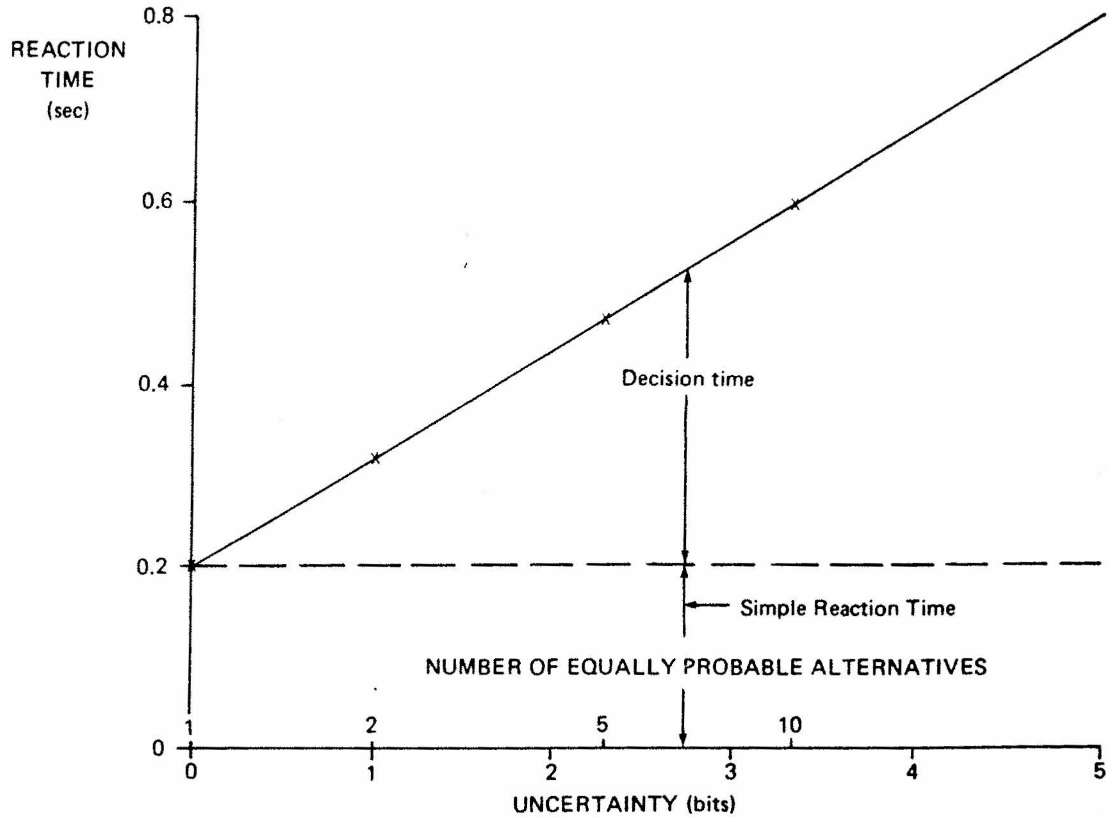
The fact that there is little reported in the literature on incremental times for recognition is because it is difficult to isolate that element of the information gathering process. At best, longer recognition or perception times can only be identified by increased reaction times.

Decision Time

During the decision period, drivers integrate the information which they have detected and recognized with their knowledge of alternative actions to arrive at a selected speed and/or path. In this process, they draw on their driving experience to identify alternative courses of action, evaluate the probability of success, and select the most appropriate course of action.

The literature reveals little in the way of data identifying the amount of time consumed by motorists for the decision-making process. It has been shown that decision time increases linearly with uncertainty or the increase in equally probable alternatives (7). This point is illustrated by Figure 2, where it can be seen that decision time is zero for a simple reaction situation (e.g., verbal response to a signal where there is no uncertainty and, therefore, no decision required), but increases to 0.4 seconds when faced with ten alternatives of equal probability. Of course, this data is for a laboratory condition, and it is not known how decision time increases with increasing complexity of the driving task.

Data are not available to indicate how much time is used by drivers during the decision-making component, especially in a complex environment. However, Forbes and Katz (20) note that "... whenever the driver must judge a complex set of visual or other stimuli and make choices, judgements and decisions, his response time may increase to 2, 3, 5, or even 10 or more seconds. Such judgements are commonly required in overtaking and passing on two-lane highways and it may be involved in multiple ramps, islands at intersections, multiple toll booth approaches and the like."



Source: Cumming (7).

Figure 2. Choice Reaction Time

Response Time

The fourth component of the model is response time. It is the period of limb movement (i.e., removing the foot from the accelerator to step on the brake or initiation of steering wheel rotation) after the selected path and/or speed has been chosen. As such, it is the last of the pre-maneuver tasks.

Once again, it is difficult to find data dealing exclusively with the response component (as defined here). However, there are at least two studies which consider a combination of decision plus response times.

Eberhard (21), in developing lead distances for in-vehicle directional information display, estimated that the decision and response times for a lane change maneuver could range from 4.0 to 20.5 seconds when there are other vehicles present, to 2.7 to 14.9 seconds without any other vehicles. The spread in both cases is attributable to modifying conditions of age, visibility, speed, drugs, alcohol, noise level, information load, etc. The times include periods for searching for other vehicles and identifying and waiting for gaps. For a speed change response, Eberhard shows a range of 0.94 to 6.00 seconds for deceleration and 0.71 to 4.25 seconds for acceleration.

Robinson, et al. (5) conducted a controlled field study where drivers were told to make lane changes to the left or right. The study resulted in mean times for decision and response (initiation of turn) as shown in Table 3.

Table 3

Mean Time (seconds) for Segments of Search

Sequence	Merge Right		Merge Left	
	Traffic	No Traffic	Traffic	No Traffic
Total Time (command to initiation of turn)	6.10	3.69	4.53	3.37
Visual input time (mirrors, back, side)	1.90	1.25	1.79	0.99
Visual loss due to eye-head movement	0.79	0.56	0.68	0.43
Remaining visual input time (road ahead, traffic, etc.)	3.41	1.88	2.06	1.95

Source: Robinson, et al., (5).

There is an extensive amount of literature dealing with reaction times, which are defined by the model as the sum of all the pre-maneuver components: detection, recognition, decision, and response. Many of these studies reflect simulated conditions with alerted motorists. For example, Ohio found the average brake reaction time to be 0.57 seconds for men and 0.62 seconds for women, but acknowledged that this is less than expected because of the anticipation of the test subjects (22).

Johannson and Rumar (8) in a recent study determined brake reaction times in a dynamic situation. Based on a sample of 321 drivers, they found that reaction times ranged from 0.3 to 2.0 seconds, with a median of 0.66 seconds and 85th percentile of 0.95 seconds. Since the test subjects were in an alerted condition, they suggested a correction factor of 135 percent, which would raise the 85th percentile figure to 1.28 seconds.

Mullin (18) notes that typical reaction time in an urban setting is lower (0.75 seconds) than for a rural setting (2.5 seconds), presumably because of the higher level of driver attentiveness in the urban areas. The 3/4 second reaction time cited for urban areas presupposes only one hazard, however.

Maneuver Time

The final component of the hazard avoidance process is the evasive or corrective maneuver. It involves a change in path and/or speed, depending upon the nature of the hazard. By change in path it is assumed that a lane change would be the selected maneuver.* Such an action would be appropriate for the following types of hazards:

- exit lane drop
- pavement width transition
- left-hand exits
- complex interchanges
- left and right turn lanes at intersections
- detours or construction areas
- fixed or moving object in lane.

Times for changing lanes (from initiation of maneuver to full placement within the adjacent lane) have been found to vary from 2 to 4.5 seconds, depending on speed and maneuverability of the vehicle (23). Generally, it can be assumed that lane change times decrease with increasing speeds.

The other type of corrective maneuver is a speed change, which in most cases would be deceleration. Speed reduction would be the required action for the following types of hazard:

- horizontal curve
- railroad-highway grade crossings
- detours and construction areas
- narrow bridges
- slippery pavement areas
- toll booths.

*Swerving off the road into the shoulder or median would be a change in path, but it is considered a drastic evasive action to avoid an impending collision.

By the definition of decision sight distance the maneuver is to be made safely and efficiently, so a comfortable deceleration rate of 9 feet per second per second (2.7 m/s^2) appears to be appropriate (24). The resultant times for completing the deceleration maneuver depends on the original and selected speed.

IV. PRELIMINARY DECISION SIGHT DISTANCE VALUES

From the discussion of the literature on decision sight distance parameters, it is clear that there are gaps which make it difficult to quantify distance values for various conditions. Throughout this analysis, it has been noted that there are many variables which can influence each of the components in the detection through maneuver process. Driver capabilities, design features, and traffic operation factors are three variables which can be expected to influence decision sight distance. Unfortunately, the state-of-the-art is not sufficiently advanced to quantitatively describe how these and other factors may affect each component of the model.

At best, a range of values can be developed using the literature findings as a basis. Such an approach has been followed in preparing Table 4, which shows the preliminary decision sight distance values for various design speeds.

As the table indicates, the range of values was derived from a summation of pre-maneuver and maneuver times converted into distance. Pre-maneuver time is the time required for a driver to process information relative to a hazard. It consists of the time to: a) detect and recognize the hazard, and b) decide the proper maneuver and initiate the response.

- Detection and Recognition Time – these two elements of the information handling process include time periods for latency (delay between the time the hazard is visible and the time the eyes begin to move), eye movement to hazard, eye fixation, and finally, recognition or perception of the hazard. Time for these elements increases with the complexity and number of hazards and with increasing vehicle speeds. A maximum of 2 seconds has ben chosen for higher speeds (25). However, longer times could be possible if the driver is inattentive or if expectancies are violated.

- Decision and Response Initiation Time – the next steps in the process are to identify the alternative maneuvers, select one, and then to initiate the required action. Since a lane change maneuver is likely and more time is consumed changing lanes than for a simple speed reduction, a lane change maneuver is assumed. The time to decide on the maneuver, search for acceptable gaps, and initiate the action can range from 2 to 7.1 seconds (5). (Longer times can occur if the volumes are high, or if it is required to change two or more lanes.)

The final element is the maneuver time which, based on existing data (23) is assumed to be between 3.5 and 4.5 seconds, increasing with decreasing speed.

The measurement of these decision sight distances should be from the height of the eye, 3.75 feet (1.14 m) to the road surface, since in most cases the hazard is a roadway condition.

Table 4

Preliminary Decision Sight Distance Values

Design Speed (mph)	Times (Seconds)				Decision Sight Distance (ft)	
	Pre-Maneuver		Maneuver (Lane Change)	Summation	Computed	Rounded For Design
	Detection & Recognition	Decision & Response Initiation				
30	1.5	4.2 – 6.6	4.5	10.2 – 12.6	449 – 554	450 – 550
40	1.5	4.2 – 6.6	4.5	10.2 – 12.6	559 – 739	575 – 750
50	1.5	4.2 – 6.6	4.0	9.7 – 12.1	711 – 887	725 – 900
60	2.0	4.7 – 7.1	4.0	10.7 – 13.1	942 – 1153	950 – 1150
70	2.0	4.7 – 7.1	3.5	10.2 – 12.6	1057 – 1294	1050 – 1300
80	2.0	4.7 – 7.1	3.5	10.2 – 12.6	1197 – 1478	1200 – 1475

1 mph = 1.609 km/h
1 ft = 0.3048 m

V. FIELD VALIDATION OF DECISION SIGHT DISTANCE

Introduction

In developing the decision sight distance values, an additive model was employed based on a conceptualization of the hazard avoidance process. While a significant amount of research has dealt with this aspect of the driving task, the existing literature was only marginally adequate for quantifying certain portions of the process and ultimately for estimating decision sight distance values. Currently, no field work has been performed to operationally validate decision sight distance values derived from the literature.

Objective

Recognition of the need for field validation brought about Phase II of the project. Phase II was a field study in a true-life operational setting for the purpose of "validating" the proposed values. In a sense, then, the evaluation is to test the values to determine if they have operational validity.

Study Design

Methodology

The methodology proposed for conducting this field validation was developed around the hazard avoidance process model presented in Section III. This model was identified as a five-phase process as follows:

- detection
- recognition
- decision
- response initiation
- avoidance maneuver.

Using this model, sight distance criteria were recommended by integrating results of several studies which dealt with one or more of these phases (see Table 4). However, much of the data was based on laboratory experiments and, in some cases, estimates. Therefore, the field experiments in this study were designed to develop "real-life" time values for these phases.

It was not feasible (within the level-of-effort limitation) nor practical to identify time elements for each distinct phase. Rather, the field experiment was designed to develop time estimates for the combinations of:

- detection and recognition – time elements t_0 to t_2
- decision and response initiation – time elements t_2 to t_4
- avoidance maneuver – time elements t_4 to t_5.

Simply stated, the experimental plan was to conduct field experiments using subject drivers under real operating conditions in order to validate or modify those time increments in Table 4.

The test procedure can be described as follows. A test subject was asked to drive over a course and to respond to certain geometrics which necessitated a change in path and possibly speed in order to maintain his/her destination objective. The responses sought included his/her initial sighting of the geometric feature in question, the moment of initiation of path and/or speed change, and finally, the time used to complete the maneuver.

The exact procedure can be described by the following scenario. The test subject, after an initial briefing and a pre-test driving exercise to gain familiarity with the vehicle and the procedure, was given instructions to proceed to a destination. A required route and destination point were discussed over a map. He/she was instructed to maintain a position in the right lane at all times (unless otherwise instructed) and to drive "normally." Maintenance of a position in the right lane exposed the subject to geometric situations (lane drops, width transitions, etc.) which required him/her to change lanes and/or modify the speed of the vehicle in order to maintain the required course.

Upon approach to the situation, one of the two experimenters activated the instrumentation system and recorded the point where the situation was first visible – time reference t_0 – this location was well marked off the side of the road. The second input (t_2) occurred when the subject responded that he/she saw the situation in question. This response was initially made by pressing the horn (deactivated for noise but connected to the instrumentation system) and then followed by a vocal response explaining what was seen. The next event recorded by the experimenter occurred when the subject driver initiated a steering wheel and/or speed change. This action signaled time increment t_4. The final event recorded by the experimenter occurred when the maneuver, e.g., lane change, was completed (time t_5). Further details related to this study metholology and procedure are outlined below.

Test Subjects

Subjects were selected for testing, based on the following criteria:

- had no or very limited exposure to the test sites
- approximately five (5) from the 16-39 age group, twelve (12) from the 40-59 age group, and three (3) 60 years old or older
- 8-10 males and 10-12 females
- valid drivers licenses
- visual acuity corrected to licensing standards
- no physical impairments.

Test subjects were obtained through advertising in local newspapers.

Because a few of the subjects had difficulty negotiating the course and following instructions, quantitative data from 19 of the 22 subjects originally selected was finally used in the analysis. The distribution by sex and age was as follows:

		Number	Percent
Sex	Male	11	58
	Female	8	42
	Total	19	100%
Age	16-39	6	32
	40-59	8	42
	>60	5	26
	Total	19	100%

Test Course and Study Sites

The test course was approximately 25 miles (40 km) long and covered a section of I-495 (Capital Beltway) in the Virginia and Maryland suburbs of Washington, D.C. and sections of I-270 and two arterials in Maryland. The course included eight data collection sites with different geometric features, as follows:

1. *Lane drop exit* – Route 123 off of NB I-495
2. *Mainline lane drop* – NB I-495 just past the George Washington Parkway
3. *Lane split from 4 lanes to 2 lanes each* – I-495 and I-270
4. *Lane drop exit* – Wisconsin Avenue exit off of EB I-495
5. *Lane drop exit* – Montrose Road exit off of NB I-270
6. *Lane reduction prior to intersection* – EN approach of Route 28 at the intersection with Route 355
7. *Left turn lanes with lane reduction prior to intersection* – SB approach of Route 355 at Route 28
8. *Lane drop exit* – River Road exit off of SB I-495.

A more complete description of each site is found in the discussion of each in Appendix A. As noted earlier, the test subject was given a destination for each section of the course and an orientation using a highway map. Schematic diagrams for each of the sites are included as part of Appendix A.

For each site, a reference point was chosen as the indicator of the hazard. In most cases, this was a physical feature of the highway, e.g., the exit gore, which was in direct view of the motorist.

To determine the point of maximum sight distance, two observers traversed the site and indicated where they were first able to see the predetermined hazard. These distances are noted on the site diagrams in Appendix A.

Data Collection Instrumentation System

The requirement for data collection necessitated the use of an instrumented vehicle. The basic requirements of the data collection system were:

1. A method of recording the time, longitudinal position, and speed of the vehicle during test runs.
2. A means of determining the time and location when several responses are made by the subject driver.
3. A method for the experimenter to make inputs to the recording system.

To satisfy these requirements, an instrumentation system was developed consisting of the following components:

- *Event Recorder.* The event recorder used was a 60 channel digital unit which records the identification of any channel which is activated and the time to 0.002 seconds. The recording medium was a standard seven-track computer tape. Twelve inputs were used: ten pushbuttons for the experimenter's keyboard, the horn ring of the vehicle, and a signal every ten feet from a fifth wheel. The recorder was battery-powered, and was located in the vehicle behind the rear seat where it could not distract the driver.

- *Fifth Wheel.* The location of the vehicle at any moment depended on an accurate, continuous measurement of distance traveled. Therefore, a fifth wheel was adapted to the event recorder for this purpose. Every ten feet (3 m) of travel the time was recorded, which permitted a precise measurement of speed as well as distance.

- *Experimenter Keyboard.* A ten-button keyboard was constructed for use by the experimenter for event input into the event recorder. While only eight of the keys were required, additional capability was provided for flexibility. These keys were used to mark the occurrence of specific events during a trial run. These included

    1. Start of course segment
    2. End of course
    3. Reference point arrival
    4. Start of subject maneuver
    5. End of subject maneuver
    6. Negate the last input
    7. Subject failed to negotiate the course
    8. Subject failed to respond to a potential hazard situation.

- *Driver Response Activator.* One of the events to be recorded required a response input by the subject driver. After considering the horn, turn signal, high-beam button, and several arrangements of switches, the horn was selected as being the least distractive to the driver and easiest to operate. The horn in the test vehicle required light pressure for activation, and a horn relay mounted in the dashboard provided an audible feedback for the subject and the experimenter. The horn itself was disconnected to avoid distraction and interference with other vehicles.

- *Movie Camera.* In order to provide a visual record of each test run, a Super 8mm movie camera was mounted on the top of the vehicle. The camera ran continuously during the test run at a speed of 1.5 frames per second. At 50 mph (80.5 km/h), this allowed a visual record of the field of view in front of the test vehicle every 110 feet (33.5 m).

The test vehicle selected for use in this study was a 1977 Dodge Aspen station wagon. A station wagon was necessary to house the event recorder for easy access by the experimenter. This is an intermediate size vehicle with power steering and a 6-cylinder engine. Figure 3 shows photographs of the various components of the instrumentation system.

Data Processing

Tapes generated by the instrumented vehicle were processed by a computer program which identified the events recorded during each segment of each subject trial run. Each event was associated with the event time, distance from the course reference point, and speed of the vehicle at the time of the event. Distance was recorded every 10 feet (3.0 m), permitting accurate interpolation of the event distance to the nearest foot and precise calculation of vehicle speed. The computer program produced a plot of speed along with the printout of events as they occurred. Figure 4 illustrates the form of the printout produced by the program.

From these computer printouts, times, distances, and speeds were extracted and recorded on data sheets. Also included on the data sheets was information on the test subject and the estimated "level of service" during the test run. The final step in the data processing was to compute several statistics for the various response times.

Data Analysis

As noted earlier, the main purpose of this experiment was to test the validity of the preliminary decision sight distance criteria as established from the literature review. To do this, each element of the hazard avoidance for which data was collected was compared against the recommended values in Table 4. In making this comparison, it should be noted that six of the eight sites (site numbers 1 through 5 and 8) were on a freeway facility at speeds of 50 to 55 mph (80.5 to 88.5 km/h), and the other sites were at urban intersections with speds of 30 mph (48.3 km/h) or less.

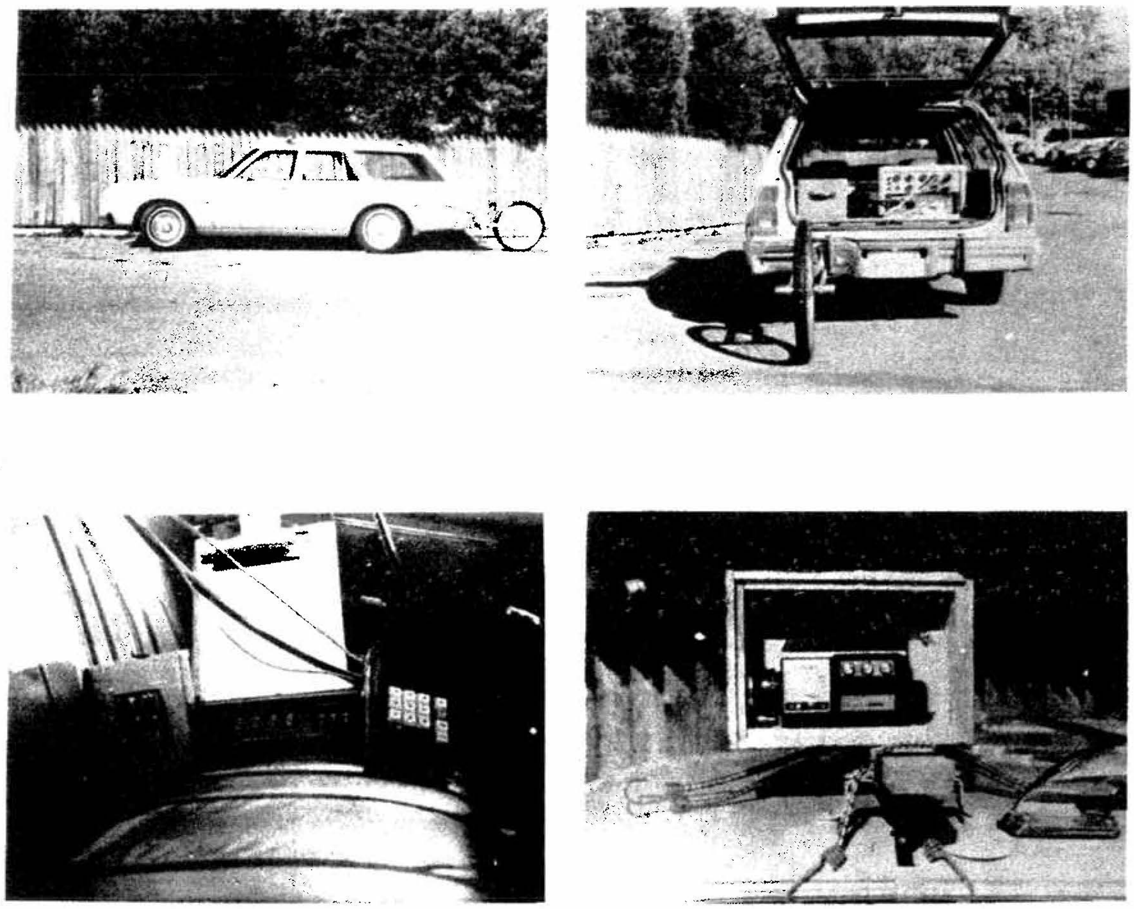


Figure 3. Illustrations of Instrumentation System

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                                          PROJECT REVIEW

              REVIEW DATA SUBJECT 1, OCT 4, 1977, EUGENE RAENES
                    Time (Seconds)                                                  Time (Seconds)
EVENT MESSAGES      of Response   Distance (Feet)   Time of Day  SPEED, TIME AND DISTANCE   into Course   Total Distance (Feet)   Speed M.P.H.
                                  into Course                0    5   10   15   20   25   30   35   40   45   50   55   60
START OF COURSE                   0000,   .0      3422   0955,57.3   0000,   .5   94050 ----+----I----5----  *  --6--
                                                         0955,57.9   0000,  1.2   94110 ----+----I----5----  *  --6--
+++++ +++++  COURSE 3  +++++ +++++  0000,  1.7     139   0955,58.5   0000,  1.9   94160 ----+----I----5----  *  --6--
                                                         0955,59.1   0000,  2.4   94210 ----+----I----5----  *  --6--
+++++ +++++  COURSE 3  +++++ +++++  0000,  4.2     352   0957, 1.5   0000,  4.8   94410 ----+----I----5----  *  --6--

                              t0                         0957, 6.4   0000,  9.6   94810 ----+----I----5---  *  ---6--
                                                         0957, 7.0   0000, 10.2   94860 ----+----I----5---  *  ---6--
SIGHT DISTANCE MARKER             0000,10.8       889    0957, 7.6   0000, 10.8   94910 ----+----I----5---  *  ---6--

                              t2                         0957,14.5   0000,17.7    95460 ----4----I----5-  *  I----6--
  HORN       HAZARD SIGHTED       0000,18.0      1473    0957,15.1   0000,18.3    95510 ----4----I----5-  *  I----6--
                                                         0957,15.7   0000,19.0    95560 ----+----I----5-  *  I----6--

                              t4                         0957,19.8   0000,23.0    95860 ----4----I-  *  5----I----6--
  BEGINNING OF MOVEMENT.          0000,23.2      1857    0957,20.5   0000,23.7    95910 ----+----I-  *  5----I----6--
                                                         0957,21.2   0000,24.4    95960 ----+----I-  *  5----I----6--

                              t6                         0957,24.7   0000,28.0    96210 ----4----I-  *  5----I----6--
   END OF MOVEMENT                0000,28.2      2210    0957,25.4   0000.28.7    96260 ----4----I-  *  5----I----6--

                                                         0957,31.7   0000,34.9    96710 ----+----I--  *  ----I----6--
 END OF COURSE                    0000,35.3      2722    0957,31.7   0000,34.9    96730 ----+----I--  *  ----I----6--
```

Figure 4. Example of Computer Printout for One Site

Detection and Recognition Phase

The procedure for identifying the amount of time it took for the subject driver to recognize a hazard requiring an avoidance maneuver was to have the subject depress the horn rim when the hazard was "recognized," followed immediately by a vocal response. The difference between this time point (identified as t_2 on the computer printout, see Figure 4) and the maximum sight distance point (t_0 on the computer printout) was determined to be the detection plus recognition time.

The detection plus recognition time for all 19 subjects and eight sites are shown in Table 5. This table also shows five statistics – mean, standard deviation, variance, and maximum/minimum values – for the columns (each site, all subjects), rows (each subject, all sites), and for all data. A minus one-tenth (–0.1) indicates no data, which resulted if there was an experimenter error or, more commonly, when the subject recognized the hazard prior to the maximum sight distance point. In the latter case this would mean the subject was recognizing other cues as an indication of the need for a change in path. These other cues could have been signs or pavement markings.

The grand mean for all values of recognition times is 5.7 seconds, with a standard deviation of 4.6 seconds. The lowest observed time was 0 seconds, and the highest was 20.0 seconds. The low value of 0 seconds is misleading since it indicates that the subject recognized the hazard exactly at the point of maximum sight distance, while in fact the subject responded to the solid lane line on the left as the hazard indicator.

With respect to the high value of 20.0 seconds, it should be noted that this value occurred for site number 8, where all of the values were much higher than the mean. The subjects took a long time recognizing this site as an exit lane drop because of poor markings and signing, and its deceptive view (see more detailed discussion, Appendix B).

A more meaningful range of recognition time is provided by the standard deviation, which indicates that two-thirds of the subjects responded in 1.1 to 10.3 seconds. The values used for this phase in the recommended criteria were 1.5 to 2.0 seconds (see Table 4).

Two factors can be suggested as reasons for the observed decision plus recognition times being longer than the recommended values:

1. In order to signal their recognition, the subjects were to press the horn. This motor response could have added as much as one second to the recognition time, depending upon how adept and responsive the subject was.

Table 5

Detection and Recognition Times

SUBJ	SITE 1	SITE 2	SITE 3	SITE 4	SITE 5	SITE 6	SITE 7	SITE 8	ROW SUMMARIES RESP.	MEAN	STD.DEV.	VARIANCE	MAX	MIN
1	0.8	-0.1	-0.1	-0.1	4.0	-0.1	-0.1	-0.1	2	2.40	2.2627	5.1200	4.0	0.8
2	1.3	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	1	1.30	0.0000	0.0000	1.3	1.3
3	-0.1	-0.1	-0.1	-0.1	-0.1	4.9	-0.1	-0.1	1	4.90	0.0000	0.0000	4.9	4.9
4	0.0	1.0	-0.1	-0.1	3.9	-0.1	-0.1	-0.1	3	1.63	2.0257	4.1033	3.9	0.0
5	-0.1	2.7	6.5	-0.1	2.6	5.1	-0.1	14.1	5	6.20	4.7149	22.2300	14.1	2.6
6	-0.1	1.9	-0.1	-0.1	4.5	-0.1	-0.1	11.3	3	5.90	4.8539	23.5600	11.3	1.9
7	-0.1	3.4	6.5	-0.1	5.0	-0.1	-0.1	14.4	4	7.32	4.8836	23.8492	14.4	3.4
8	3.2	3.6	3.6	-0.1	4.0	7.1	-0.1	18.0	6	6.58	5.7711	33.3057	18.0	3.2
9	-0.1	2.1	7.5	-0.1	3.7	4.6	7.8	9.0	6	5.78	2.7081	7.3337	9.0	2.1
10	-0.1	0.2	-0.1	-0.1	6.6	-0.1	-0.1	15.2	3	7.33	7.5268	56.6533	15.2	0.2
11	2.3	1.3	5.8	-0.1	6.1	-0.1	9.5	-0.1	5	5.00	3.2818	10.7700	9.5	1.3
12	7.2	1.6	-0.1	-0.1	5.6	3.8	-0.1	-0.1	4	4.55	2.4076	5.7967	7.2	1.6
13	8.7	-0.1	6.6	0.3	7.4	-0.1	-0.1	-0.1	4	5.75	3.7350	13.9500	8.7	0.3
14	3.0	0.7	-0.1	-0.1	5.9	-0.1	-0.1	18.2	4	6.95	7.7959	60.7766	18.2	0.7
15	6.6	1.4	-0.1	-0.1	5.7	5.4	6.7	-0.1	5	5.16	2.1755	4.7330	6.7	1.4
16	1.5	1.1	2.5	-0.1	2.6	-0.1	-0.1	17.0	5	4.94	6.7722	45.8630	17.0	1.1
17	0.7	1.3	7.2	-0.1	8.2	-0.1	3.1	13.5	6	5.67	4.9082	24.0907	13.5	0.7
18	3.5	2.6	6.6	-0.1	9.2	-0.1	-0.1	20.0	5	8.38	7.0016	49.0220	20.0	2.6
19	7.5	-0.1	2.5	-0.1	0.7	-0.1	-0.1	-0.1	3	3.57	3.5233	12.4133	7.5	0.7
STATISTICS FOR TABLE:									74	5.69	4.5640	20.8304	20.0	0.0

COLUMN SUMMARIES

	SITE 1	SITE 2	SITE 3	SITE 4	SITE 5	SITE 6	SITE 7	SITE 8
RESPONSES	13	14	10	1	17	6	4	10
MEAN	3.56	1.78	5.53	0.30	5.04	5.15	6.77	15.07
STD.DEV.	2.9480	0.9978	1.9149	0.0000	2.1535	1.1005	2.7072	3.3556
VARIANCE	8.6909	0.9957	3.6668	0.0000	4.6376	1.2110	7.3292	11.2601
MAXIMUM	8.7	3.6	7.5	0.3	9.2	7.1	9.5	20.0
MINIMUM	0.0	0.2	2.5	0.3	0.7	3.8	3.1	9.0

2. Although the subjects were instructed to respond "as soon as they recognized the hazard situation," it appeared that several had already formulated a decision regarding their vehicle response. This was evidenced in some cases by vehicle deceleration prior to the recognition response. Where this occurred, the recorded recognition time (t_0 to t_2) actually included all or a portion of the decision time (t_3).

Even allowing for these two factors, it appears that while the 1.5 seconds noted in Table 4 may be an adequate minimum value for some situations, there are others that require longer times. As demonstrated by the field data, it takes many drivers more than 2.0 seconds (recommended maximum value from Table 4) from the moment a potential hazard comes within their sight line to detect and recognize a highway situation as such, despite the fact that the geometry view is enhanced by signs and markings.

Decision and Response Phase

The second part of the pre-maneuver phase of the hazard avoidance process is the decision and response period. This is the period when the driver decides on the proper course of action (speed and/or path change), and initiates the required maneuver. From the experiment, this phase was defined as the difference in time from the moment of recognition (time t_2 on the computer printout, see Figure 4) to the initiation of the lane change maneuver (time t_4 on the printout).

Table 6 shows the results for all of the test subjects and sites, with the statistics as described previously. Again, a minus value indicates that there was no data for one or several reasons.

The overall statistics reveal that the grand mean was 4.8 seconds, with a standard deviation of 4.7. The observed values ranged from 0.5 seconds to 36.1 seconds.

For this phase, there was much less variability in observed times. If site number 6 (one of the two urban sites) is eliminated, the site (column) means range from 2.71 to 6.41 seconds. Also, if the data for subject number 15 is omitted, the subject (row) means vary from 2.40 to 6.96 seconds. Finally, it is noted that two-thirds of the subjects had times between 0.16 and 9.55 seconds.

The observed values tend to support the recommended times found in Table 4 – 4.2 to 7.1 seconds. As for the previous phase, a range of values is appropriate to accommodate the variation in decision complexity, surrounding traffic, driver experience and ability for different types of situations.

Table 6

Decision and Response Times

									ROW SUMMARIES					
SUBJ	SITE 1	SITE 2	SITE 3	SITE 4	SITE 5	SITE 6	SITE 7	SITE 8	RESP.	MEAN	STD.DEV.	VARIANCE	MAX	MIN
1	1.4	4.5	-0.1	6.9	2.7	19.3	-0.1	-0.1	5	6.96	7.2006	51.8480	19.3	1.4
2	3.6	-0.1	3.9	-0.1	-0.1	-0.1	10.3	-0.1	3	5.93	3.7846	14.3233	10.3	3.6
3	3.6	-0.1	4.2	10.3	3.1	8.3	-0.1	-0.1	5	5.90	3.2070	10.2850	10.3	3.1
4	1.9	1.4	2.9	1.2	1.9	-0.1	-0.1	6.4	6	2.62	1.9447	3.7817	6.4	1.2
5	5.0	1.5	1.6	9.8	2.1	18.5	5.3	1.1	8	5.61	5.9739	35.6870	18.5	1.1
6	3.5	3.3	-0.1	3.3	1.9	-0.1	3.2	2.3	6	2.92	0.6524	0.4257	3.5	1.9
7	4.1	1.5	3.0	8.7	3.7	-0.1	3.0	2.6	7	3.80	2.3137	5.3533	8.7	1.5
8	2.8	2.6	2.7	4.9	3.9	0.7	-0.1	3.0	7	2.94	1.2895	1.6629	4.9	0.7
9	4.8	2.3	3.3	5.5	8.0	2.6	6.6	13.4	8	5.81	3.6463	13.2955	13.4	2.3
10	5.8	3.5	11.7	7.9	2.9	-0.1	-0.1	4.4	6	6.03	3.3031	10.9106	11.7	2.9
11	4.2	3.4	5.0	4.3	6.8	-0.1	8.2	4.5	7	5.20	1.6902	2.8567	8.2	3.4
12	2.9	4.0	-0.1	5.5	8.9	10.3	-0.1	-0.1	5	6.32	3.1721	10.0620	10.3	2.9
13	1.9	-0.1	2.5	2.2	3.0	-0.1	-0.1	-0.1	4	2.40	0.4690	0.2200	3.0	1.9
14	3.1	2.5	-0.1	2.6	2.3	-0.1	-0.1	1.1	5	2.32	0.7430	0.5520	3.1	1.1
15	1.4	3.7	-0.1	11.7	4.7	36.1	3.5	-0.1	6	10.18	13.1749	173.5777	36.1	1.4
16	1.3	1.7	8.4	9.4	0.6	-0.1	-0.1	0.5	6	3.65	4.1030	16.8350	9.4	0.5
17	4.7	3.1	5.2	3.7	14.4	-0.1	2.8	4.7	7	5.51	4.0181	16.1448	14.4	2.8
18	2.0	1.7	4.0	16.2	1.8	-0.1	-0.1	2.1	6	4.63	5.7302	32.8346	16.2	1.7
19	1.3	-0.1	4.5	1.3	2.6	-0.1	-0.1	-0.1	4	2.43	1.5130	2.2892	4.5	1.3

STATISTICS FOR TABLE:

RESP.	MEAN	STD.DEV.	VARIANCE	MAX	MIN
111	4.85	4.6993	22.0831	36.1	0.5

COLUMN SUMMARIES

	SITE 1	SITE 2	SITE 3	SITE 4	SITE 5	SITE 6	SITE 7	SITE 8
RESPONSES	19	15	14	18	18	7	8	12
MEAN	3.12	2.71	4.49	6.41	4.18	13.69	5.36	3.84
STD.DEV.	1.4081	1.0127	2.6369	4.0439	3.3815	12.1730	2.7841	3.4805
VARIANCE	1.9829	1.0255	6.9530	16.3528	11.4344	148.1815	7.7512	12.1136
MAXIMUM	5.8	4.5	11.7	16.2	14.4	36.1	10.3	13.4
MINIMUM	1.3	1.4	1.6	1.2	0.6	0.7	2.8	0.5

Maneuver Phase

The final phase of the hazard avoidance process is the actual maneuver for all of the eight sites which required a lane change. However, some speed reductions were also observed in connection with the lane change, even during the decision and response initiation phase. The maneuver time was determined by subtracting the time when the maneuver was completed, i.e., when the vehicle was positioned in the next lane (time t_5 on the printout) and when the maneuver was initiated (time t_4).

Table 7 provides the results of data collected for all sites and subjects with the appropriate statistics. As before, a minus value indicates that no data was collected for one of several reasons. Sites 6 and 7, the urban intersections, have several missing data points because the maneuver phase was frequently curtailed by traffic stopping in queue due to the traffic signal (see site discussions, Appendix B).

The grand mean for all observed times was 4.6 seconds with a standard deviation of 1.7, which indicates that two-thirds of the subjects had maneuver times between 2.9 and 6.3 seconds. The two urban intersection sites had the highest values at 6.6 and 5.8 seconds. Although not of the same magnitude as those values recommended in Table 4 (4.5 seconds at 30 mph [48.3 km/h] to 3.5 seconds at 80 mph [128.7 km/h]), they are higher than the freeway sites where the speeds were 50 to 55 mph (80.5 to 88.5 km/h). The longer time for lane changing at lower speeds probably reflects the impedance of other traffic.

For the six freeway sites the range of the mean maneuver times is 4.04 to 5.06 seconds, which is very close to the recommended value of 4.0 seconds at 50 – 60 mph (80.5–96.6 km/h). But again as for other phases there were several instances where higher times were observed.

Additional data on maneuver times for lane changes was obtained from film recorded field data gathered in an earlier research study at one of the study sites. Using time-lapse movie films of traffic flow in the vicinity of site #3, the I-495/I-270 split, lane maneuver times were found to average 4.2 to 4.7 seconds for the right and left lane merge, respectively. The speeds for these maneuvers ranged between 50 – 60 mph (80.5 – 96.6 km/h). From the results of these two field studies it appears that the recommended lane maneuver time could be increased to 4.5 seconds for all speeds.

Total Hazard Avoidance Process Times

Table 8 presents the total processing times which are the sums of the three component times – i.e., decision and recognition plus detection and response plus the maneuver. This table contains numerous missing data entries (denoted by –0.1) because if either the first or third phase had missing data, then the entire time processing time could not be determined.

Table 7

Maneuver Times

SUBJ	SITE 1	SITE 2	SITE 3	SITE 4	SITE 5	SITE 6	SITE 7	SITE 8	ROW SUMMARIES RESP.	MEAN	STD.DEV.	VARIANCE	MAX	MIN
1	4.8	6.8	-0.1	4.0	4.0	7.5	-0.1	-0.1	5	5.42	1.6316	2.6620	7.5	4.0
2	4.0	-0.1	5.1	-0.1	-0.1	-0.1	3.8	-0.1	3	4.30	0.7000	0.4900	5.1	3.8
3	2.8	-0.1	5.9	3.7	4.2	9.7	-0.1	-0.1	5	5.26	2.7264	7.4330	9.7	2.8
4	3.4	4.6	4.4	2.7	4.9	-0.1	-0.1	5.6	6	4.27	1.0501	1.1027	5.6	2.7
5	3.8	5.0	4.8	3.7	3.3	-0.1	6.8	3.8	7	4.46	1.2026	1.4462	6.8	3.3
6	3.9	5.8	-0.1	4.2	4.9	-0.1	8.4	3.7	6	5.15	1.7672	3.1230	8.4	3.7
7	4.0	4.4	4.6	5.5	4.1	-0.1	4.4	6.7	7	4.81	0.9651	0.9314	6.7	4.0
8	3.9	4.4	5.4	5.7	5.9	-0.1	-0.1	4.9	6	5.03	0.7789	0.6067	5.9	3.9
9	9.1	3.9	13.0	4.1	4.5	-0.1	-0.1	3.5	6	6.35	3.8573	14.8790	13.0	3.5
10	4.6	5.8	6.3	6.2	9.9	-0.1	-0.1	6.2	6	6.50	1.7821	3.1760	9.9	4.6
11	4.9	4.2	3.7	7.4	3.2	-0.1	4.3	5.0	7	4.67	1.3586	1.8457	7.4	3.2
12	4.3	3.8	-0.1	2.9	3.5	4.9	-0.1	-0.1	5	3.88	0.7629	0.5820	4.9	2.9
13	3.5	3.9	2.6	2.5	2.6	-0.1	-0.1	-0.1	5	3.02	0.6380	0.4070	3.9	2.5
14	4.1	3.4	3.9	3.2	4.0	-0.1	-0.1	3.9	6	3.75	0.3619	0.1310	4.1	3.2
15	3.0	5.6	-0.1	4.5	5.1	4.4	-0.1	-0.1	5	4.52	0.9783	0.9570	5.6	3.0
16	3.3	3.5	4.7	4.2	3.8	-0.1	-0.1	3.2	6	3.78	0.5776	0.3337	4.7	3.2
17	3.9	3.8	5.0	3.9	3.3	-0.1	7.3	4.3	7	4.50	1.3404	1.7967	7.3	3.3
18	4.6	3.7	3.7	3.8	4.6	-0.1	-0.1	3.1	6	3.92	0.5845	0.3417	4.6	3.1
19	2.3	-0.1	2.8	0.5	3.2	-0.1	-0.1	-0.1	4	2.20	1.1916	1.4200	3.2	0.5
STATISTICS FOR TABLE:									108	4.57	1.6945	2.8712	13.0	0.5

COLUMN SUMMARIES

	SITE 1	SITE 2	SITE 3	SITE 4	SITE 5	SITE 6	SITE 7	SITE 8
RESPONSES	19	16	15	18	18	4	6	12
MEAN	4.12	4.54	5.06	4.04	4.39	6.63	5.83	4.49
STD.DEV.	1.3849	0.9926	2.4269	1.5363	1.6033	2.4595	1.9086	1.1882
VARIANCE	1.9181	0.9852	5.8897	2.3602	2.5704	6.0491	3.6427	1.4117
MAXIMUM	9.1	6.8	13.0	7.4	9.9	9.7	8.4	6.7
MINIMUM	2.3	3.4	2.6	0.5	2.6	4.4	3.8	3.1

Table 8

Total Processing Times

SUBJ	SITE 1	SITE 2	SITE 3	SITE 4	SITE 5	SITE 6	SITE 7	SITE 8	ROW SUMMARIES RESP.	MEAN	STD.DEV.	VARIANCE	MAX	MIN
1	7.0	-0.1	-0.1	-0.1	10.7	-0.1	-0.1	-0.1	2	8.85	2.6163	6.8450	10.7	7.0
2	8.9	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	1	8.90	0.0000	0.0000	8.9	8.9
3	-0.1	-0.1	-0.1	-0.1	-0.1	22.9	-0.1	-0.1	1	22.90	0.0000	0.0000	22.9	22.9
4	5.3	7.0	-0.1	-0.1	10.3	-0.1	-0.1	-0.1	3	7.53	2.5423	6.4633	10.3	5.3
5	-0.1	9.2	12.9	-0.1	8.0	-0.1	-0.1	19.0	4	12.27	4.9446	24.4492	19.0	8.0
6	-0.1	11.0	-0.1	-0.1	11.3	-0.1	-0.1	17.3	3	13.20	3.5539	12.6300	17.3	11.0
7	-0.1	9.3	14.1	-0.1	12.8	-0.1	-0.1	23.7	4	14.97	6.1597	37.9425	23.7	9.3
8	9.9	10.6	11.7	-0.1	13.8	-0.1	-0.1	25.9	5	14.38	6.6066	43.6470	25.9	9.9
9	-0.1	8.3	23.8	-0.1	16.2	-0.1	-0.1	16.9	4	16.30	6.3409	40.2066	23.8	8.3
10	-0.1	9.5	-0.1	-0.1	19.4	-0.1	-0.1	25.8	3	18.23	8.2124	67.4434	25.8	9.5
11	11.4	8.9	14.5	-0.1	16.1	-0.1	22.0	-0.1	5	14.58	4.9937	24.9370	22.0	8.9
12	14.4	9.4	-0.1	-0.1	18.0	19.0	-0.1	-0.1	4	15.20	4.3420	18.8533	19.0	9.4
13	14.1	-0.1	11.7	5.0	13.0	-0.1	-0.1	-0.1	4	10.95	4.0862	16.6966	14.1	5.0
14	10.2	6.6	-0.1	-0.1	12.2	-0.1	-0.1	23.2	4	13.05	7.1524	51.1566	23.2	6.6
15	11.0	10.7	-0.1	-0.1	15.5	45.9	-0.1	-0.1	4	20.78	16.8933	285.3823	45.9	10.7
16	6.1	6.3	15.6	-0.1	7.0	-0.1	-0.1	20.7	5	11.14	6.6568	44.3130	20.7	6.1
17	9.3	8.2	17.4	-0.1	25.9	-0.1	13.2	22.5	6	16.08	7.1519	51.1496	25.9	8.2
18	10.1	8.0	14.3	-0.1	15.6	-0.1	-0.1	25.2	5	14.64	6.6568	44.3130	25.2	8.0
19	11.1	-0.1	9.8	-0.1	6.5	-0.1	-0.1	-0.1	3	9.13	2.3714	5.6233	11.1	6.5
STATISTICS FOR TABLE:									69	14.10	6.8245	46.5732	45.9	5.3

COLUMN SUMMARIES

	SITE 1	SITE 2	SITE 3	SITE 4	SITE 5	SITE 6	SITE 7	SITE 8
RESPONSES	13	14	10	1	17	3	2	10
MEAN	9.91	8.79	14.58	5.00	13.66	29.27	17.60	22.02
STD.DEV.	2.7125	1.4816	3.8955	0.0000	4.8590	14.5363	6.2225	3.3871
VARIANCE	7.3574	2.1951	15.1751	0.0000	23.6099	211.3032	38.7201	11.4727
MAXIMUM	14.4	11.0	23.8	5.0	25.9	45.9	22.0	25.9
MINIMUM	5.3	6.3	9.8	5.0	6.5	19.0	13.2	16.9

Due to the frequency of missing data, the statistics shown in the table may not be very representative. Only five of the eight sites had ten or more subjects with total processing times. Of these, the mean values ranged from 8.8 to 22.0 seconds. Considering all data for all sites and subjects, the grand mean was 14.1 seconds with a standard deviation of 6.8 seconds.

From the recommended values in Table 4, the total processing times should range from 9.7 to 13.1 seconds. The low side of this recommended range, i.e., 9.7 seconds, tends to be supported by results of the field data. It is interesting to note that for site #1 which had a maximum sight distance nearly equal to the recommended DSD, the total mean processing time was 9.9 seconds with a standard deviation of 2.7 seconds. At 55 mph (88.5 km/h), which is the operating speed, the total processing time would be 10.2 to 12.6 seconds, based on the recommended criteria. At this one site at least, the recommended criteria appear to have been validated.

The upper end of the total processing times recommended in Table 4 – 13.1 seconds – may be too low based on the field studies. However, from the field data it is difficult to establish where the upper limit should be set.

Summary of Results

The purpose of this second phase was to validate the preliminary decision sight distance criteria developed from the literature under actual highway situations. Validation would have been attained if one or both of the following results were found:

- The times recommended from Phase 1 for the various components of the hazard avoidance process were replicated using several subject drivers.
- At sites where the existing sight distance was shorter than the recommended decision sight distance, drivers could not negotiate the situation safely and efficiently. Conversely, at sites where sight distances was equal to or greater than the recommended DSD, drivers had no problem negotiating the required change in path and speed.

The first validation criteria was only partially met. For the detection plus recognition phase, times greater than the maximum value of 2.0 seconds were observed in many cases. However, for reasons explained earlier, the high values are not indicative of the actual time required of this phase of the hazard avoidance process. In view of the results, a range of 1.5 to 3.0 seconds seems appropriate. The lower value, suggested in Table 4, appears to be the minimum required, while 3.0 seconds would be required for more complex situations.

The results of the field data for the decision plus response time were reasonably compatible with the criteria developed in Phase 1. Although higher times were observed, it is believed that the upper range of 6.6 to 7.1 seconds, depending upon the speed, is a good design criteria for the more complex situations, while 4.2 to 4.7 seconds appears to be adequate for the less demanding situations.

The time value which was most nearly replicated was the maneuver time. The preliminary DSD criteria allows times of 4.5 seconds for 30 mph (48.3 km/h) to 3.5 seconds for 70 to 80 mph (112.7 to 128.7 km/h). Based on the results of the field experiment as well as data re-analyzed from a previous study, it appears that a value of 4.5 seconds is appropriate for speeds up to at least 60 mph (96.6 km/h). Design values for higher speeds should probably be 4.0 seconds rather than 3.5 seconds.

The second of the two validation criteria noted above was met. At sites #1, #3, #5, and #8, the maximum sight distance was greater than the DSD, and at the first three sites, the subjects successfully negotiated the course; that is, they were able to recognize the potential hazard situation and responded to it safely and efficiently. At site #8, which had the longest sight distance, several of the subjects drove across the painted gore area. This is also the site which had the longest recognition times. The reason for both ofthese occurrences is that while there was a long clear sight line of the lane drop, it was difficult to distinguish because of the misplaced signing and faded lines. At the other four sites which had inadequate sight distance, several subjects could not negotiate the site properly. (For further detail, see Discussions in Appendix A.)

VI. CONCLUSIONS AND RECOMMENDATIONS

In view of the findings of the literature synthesis and the results of field validation experiments, it is concluded that the concept of decision sight distance is operationally valid. Drivers do need sufficiently long sight distance of roadway which affords ample time to detect and recognize a potential hazard, decide on the proper course of action, and complete the required maneuver in a safe and efficient manner. This sight distance is dependent upon the driver's ability to process information and to maneuver the vehicle which in turn are related to the level of decision complexity, visual clutter and the surrounding traffic.

From the analytical and limited empirical research it is possible to recommend a range of decision sight distance values. Using a hazard avoidance model, originally developed by Baker and Stebbins (16) as a framework, decision sight distance can be quantified from the summation of times required for the sequential process involved in the detection of a hazard to the completion of a maneuver. These recommended times are shown in Table 9 and are converted into distances for various design speeds.

The recommended times have been divided into pre-maneuver and maneuver phases. Pre-maneuver is the time required for a driver to process information relative to a hazard. It consists of the time to: (1) detect and recognize the hazard, and (2) decide upon the proper maneuver and initiate the action.

- *Detection and Recognition Times* – These two elements of the information handling process include time periods for latency (delay between when a hazard is visible and when eyes begin to move), eye movement to the hazard, eye fixation and, finally, recognition or perception of the hazard. Time for these elements increases with the complexity and number of hazards and with increasing vehicle speed. A minimum of 1.5 seconds is recommended for situations with moderate complexity and visual clutter, while 3 seconds is required for more complex situations or where the hazard is particularly difficult to detect, or where driver expectancies are violated.

- *Decision and Response Initiation Time* – The second part of the pre-maneuver phase is the decision and response elements which involve selecting from alternative maneuvers and initiating the required action. The time to decide on the maneuver, search for acceptable gaps (for a lane change), and initiate the action can range from 4.2 to 7.0 seconds, again depending upon the decision complexity, motorists' attributes, and the surrounding traffic.

The second phase is the maneuver time. Since a lane change maneuver is likely and more time is consumed changing lanes than for a speed reduction, a lane change maneuver is assumed in Table 9.

Table 9

Recommended Decision Sight Distance

Design Speed (mph)	Times (Seconds)				Decision Sight Distance (Feet)	
	Pre-Maneuver					
	Detection & Recognition	Decision & Response Initiation	Maneuver	Summation	Computed	Rounded For Design
30	1.5 – 3.0	4.2 – 6.5	4.5	10.2 – 14	449 – 616	450 – 625
40	1.5 – 3.0	4.2 – 6.5	4.5	10.2 – 14	598 – 821	600 – 825
50	1.5 – 3.0	4.2 – 6.5	4.5	10.2 – 14	748 – 1027	750 – 1025
60	2.0 – 3.0	4.7 – 7.0	4.5	11.2 – 14.5	986 – 1276	1000 – 1275
70	2.0 – 3.0	4.7 – 7.0	4.0	10.7 – 14	1099 – 1437	1100 – 1450
80	2.0 – 3.0	4.7 – 7.0	4.0	10.7 – 14	1255 – 1643	1250 – 1650

1 mph = 1.609 km/h
1 ft = 0.3048 m

The last column in Table 9 shows the recommended decision sight distances. A range of values has been provided with the general guideline that the lower end is the minimum acceptable for situations of moderate complexity or visual clutter, and the upper is desirable for highly complex or cluttered locations. Unfortunately, due to the limitations of this study, it is not possible to provide specific criteria for the level of complexity or clutter.

For design purposes, decision sight distances should be from the driver's eye height to an object of *zero* height, since the driver must be able to see the entire roadway. However, a higher limit can be used if some other physical feature provides the hazard information to the driver.

Recommended Applications for Decision Sight Distance

The use of decision sight distance, specifically those values presented in Table 9, is recommended for two applications. First, it should be used in highway design, either for new facilities or reconstruction (improvement) of "below-standard" facilities. The types of locations where it should be applied are generally characterized by conditions that create the potential need for drivers to depart from simple steering and speed control maneuvers performed to follow the road. It is also recommended for use at special-feature locations where drivers could experience problems in handling information. These locations generally include

- interchanges, especially freeway-to-freeway
- intersections
- toll plazas
- pavement width reductions – lane drops
- any other location where unusual or unexpected maneuvers are required.

For all design situations the higher values are suggested for especially complex areas such as interchanges with left-hand exits or multiple exits in close proximity. The lower values should be considered minimally acceptable.

The second suggested application is for traffic control techniques at hazardous locations. More specifically, the criteria can be used to determine the need for and location of advance warning signs. For this application, decision sight distance was incorporated into the Positive Guidance process (14) to define the advance and approach zones to a hazard. The upstream edge of the approach zone is defined by the decision sight distance value for a given speed. The length of the approach zone is the difference between the Decision Sight Distance and the Stopping Sight Distance. The latter distance defines the extremity of the non-recovery zone. The advance zone is defined as an unbounded length upstream of the approach zone. The Positive Guidance process suggests different information needs depending on the zone in which first sighting of the hazard occurs:

- If the first sighting of the hazard occurs upstream of the Approach Zone and is continuous up to the hazard, there is no need for alerting information.
- When first sighting occurs in the early to mid portions of the Approach Zone, consider establishing an information need to reinforce the sighting.
- If the first perception occurs in the late stages of the Approach Zone or in the Nonrecovery Zone, the motorists should be alerted to the hazard and told of the appropriate avoidance maneuver.

In using Table 9 to determine the appropriate decision sight distance, the 85th percentile speed rather than design speed should be used. Also, while the higher values are recommended for defining the decision sight distance, the ranges are provided for the flexibility often required to physically locate advance signs.

Recommendations for Further Research

In developing the decision sight distance values, an additive model was employed based on a conceptualization of the hazard avoidance process. While a significant amount of research has dealt with this aspect of the driving task, the existing literature was only marginally adequate for quantifying certain portions of the process and ultimately for estimating decision sight distance values.

The results of the pursuant field validation confirm that decision sight distance is operationally valid. However, the data was of limited value for empirically developing decision sight distance values, because of the many confounding and uncontrollable variables such as traffic density, signing and marking treatments, navigational difficulties, etc.

In view of these shortcomings, further research is warranted to fill voids. This research should take into consideration the range of drivers' capabilities, environmental conditions and the various types of hazards which decision sight distance addresses. More specifically, further research is needed to

- provide criteria for identifying levels of decision complexity and visual noise associated with decision sight distance
- deal with urban arterials as a separate situation. Results from the field studies indicate that the recommended DSD values may not be appropriate for the urban situation
- integrate decision sight distance with the concept of information lead distance. This aspect of the problem would address how signing could compensate for inadequate DSD, the placement of advance warning signs and other traffic control requirements.

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APPENDIX A

SITE DIAGRAMS AND DISCUSSIONS

APPENDIX A

SITE DIAGRAMS AND DISCUSSIONS

Site #1

This site consists of a right hand exit lane drop occurring at the interchange on Northbound I-495 and Virginia Route 123 East (see Figure 5). Although the lane drop is clearly signed with two overhead "EXIT ONLY" guide signs, the test subjects were instructed to drive in this exit lane and respond to some other object-hazard ahead. It was predetermined that the physical gore at the exit ramp be established as the hazard, and the maximum sight distance to this hazard point was measured to be 1,000 feet (304.8 m). To maintain the proper course, the drivers would have to merge left into the through lanes. Based on Table 4, the decision sight distance for an operating speed of 55 mph (88.5 km/h) would be about 800 – 1,000 feet (243.8 – 304.8 m). Therefore, this site had adequate decision sight distance for the operating speed (but not for the design speed).

The overwhelming majority (90%) of subjects reported responding to the solid white line on the left delineating the exit lane, rather than the actual gore. In fact, 27% of the responses were a recognition of the inception of this solid line since these subjects demonstrated their first response *prior to* the predetermined maximum sight distance marker. In no case was a subject unable to successfully change to the left lane in a safe, reasonable time following recognition of a hazard-cue. Consequently, delays in completion of the total maneuver were purely a function of the traffic conditions immediately impingent upon the vehicle.

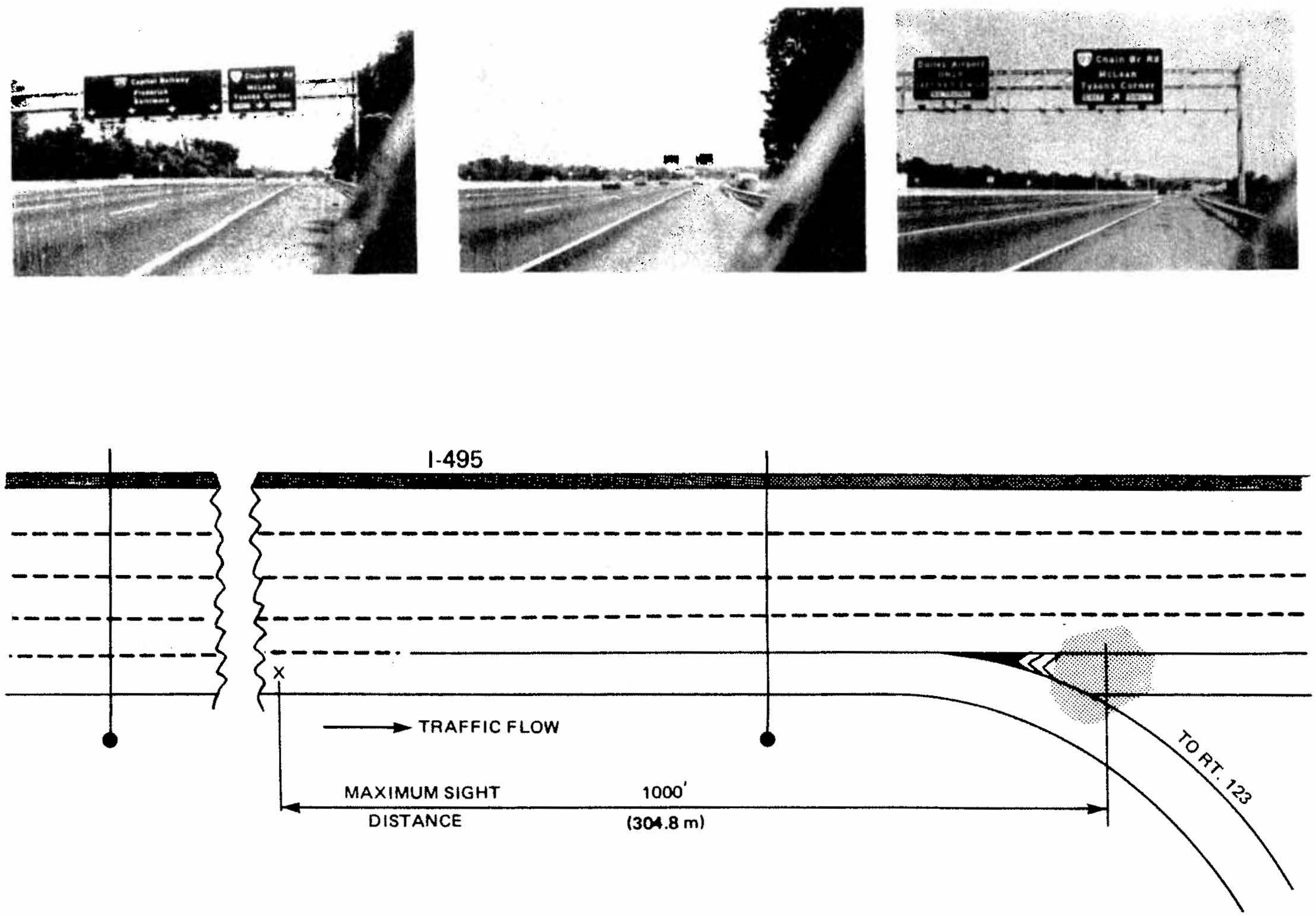


Figure 5. Schematic Illustration of Site #1

Site #2

The second site is a mainline lane drop on Northbound I-495 just past the George Washington Parkway exit ramp (see Figure 6). This merging situation is indicated by an overhead sign reading "THIS LANE ENDS," but subjects were asked to disregard this message if possible. With subjects in this right lane position, they were forced to merge left into the through lane at the lane drop area.

The beginning of the lane drop, where the lane actually terminated, was difficult to see. In fact, the maximum sight distance to this point was measured to be only 215 feet (65.5 m). This is considerably below the recommended decision sight distance of 800 – 1,000 feet (243.8 – 304.8 m) for an operating speed of 55 mph (88.5 km/h). Of course, the overhead sign which drivers could view further upstream compensates for this limited sight distance.

Most of the test subjects (65%) reported responding to the end of the dashed lane lines as an indication of the need to change their lane. The remaining 35% of respondents were obviously responding to the warning sign or, as occurred in three cases, were the victims of unforseen alterations in the nature of the test site. On one particular test day, a highway construction crew had placed an arrow flasher board and a series of traffic cones in the midst of the lane drop. These devices served to divert drivers from shoulder work being done on this day. Hence, the three drivers tested through this site very neatly responded to the arrow board as their first cue to merge left. This response was far in advance of the maximum sight distance marker. This unsolicited data on flasher boards is documentation of their extremely high target value, not only because they were reported sighted at a far distance, but also because the maneuvering time into the next left through lane was well below the average for other decision sight distance sites. Apparently the flasher board is a very strong signal to the driver that he must divert in the direction of the arrow fairly quickly. Total performance across subjects in negotiating the left lane merge was without any undue difficulty. Hence, since all subjects through the site merged safely and efficiently, those few subjected to the arrow board responded to and processed the event far in advance of the others.

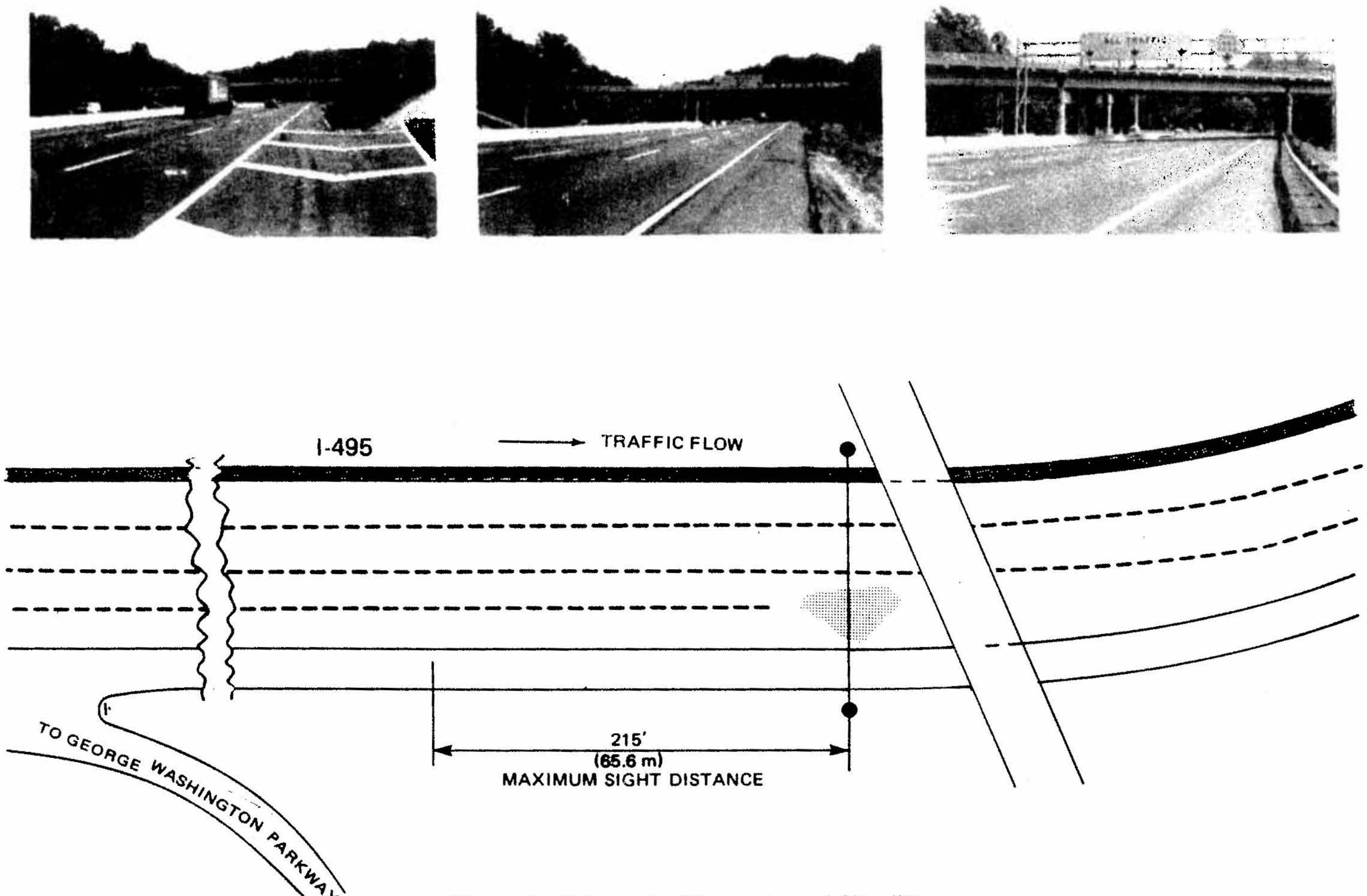


Figure 6. Schematic Illustration of Site #2

Site #3

This site is a major lane split on I-495 wherein four lanes split: two for I-495 and two to accommodate the I-270 north spur exit to the left (see Figure 7). In this case, the subject was asked to shift from his typical task instructions of driving in the far right lane to driving in the left center lane. This forced the subject to make a lane change to the right in order to continue on I-495. The hazard at the split was the physical gore itself and the maximum sight distance measured from this point was 1,800 feet (548.6 m). This is well in excess of the recommended decision sight distance of 800 – 1,000 feet (243.8 – 304.8 m) for an operating speed of 55 mph (88.5 km/h). A particularly noteworthy characteristic of this site is the very strong diagrammatic guide signing treatment preceding the actual interchange. Predisposition to the lane split became very evident in driver comments to the one mile advance guide sign.

Most drivers displayed quick recognition of the hazard situation and all successfully shifted to the right center lane to maintain their path on I-495. Some even responded before the sight distance marker (25%). In only 50% of total responses, however, did subjects report that their first cue to change their lane was sighting of the predetermined hazard, the physical gore – "CONCRETE LANES SPLITTING AHEAD." The remaining 45 – 50% used the beginning of the solid white artificial gore line as their cue. Some delays in maneuver time for a few subjects was a function of traffic density or some confusion about which direction to follow.

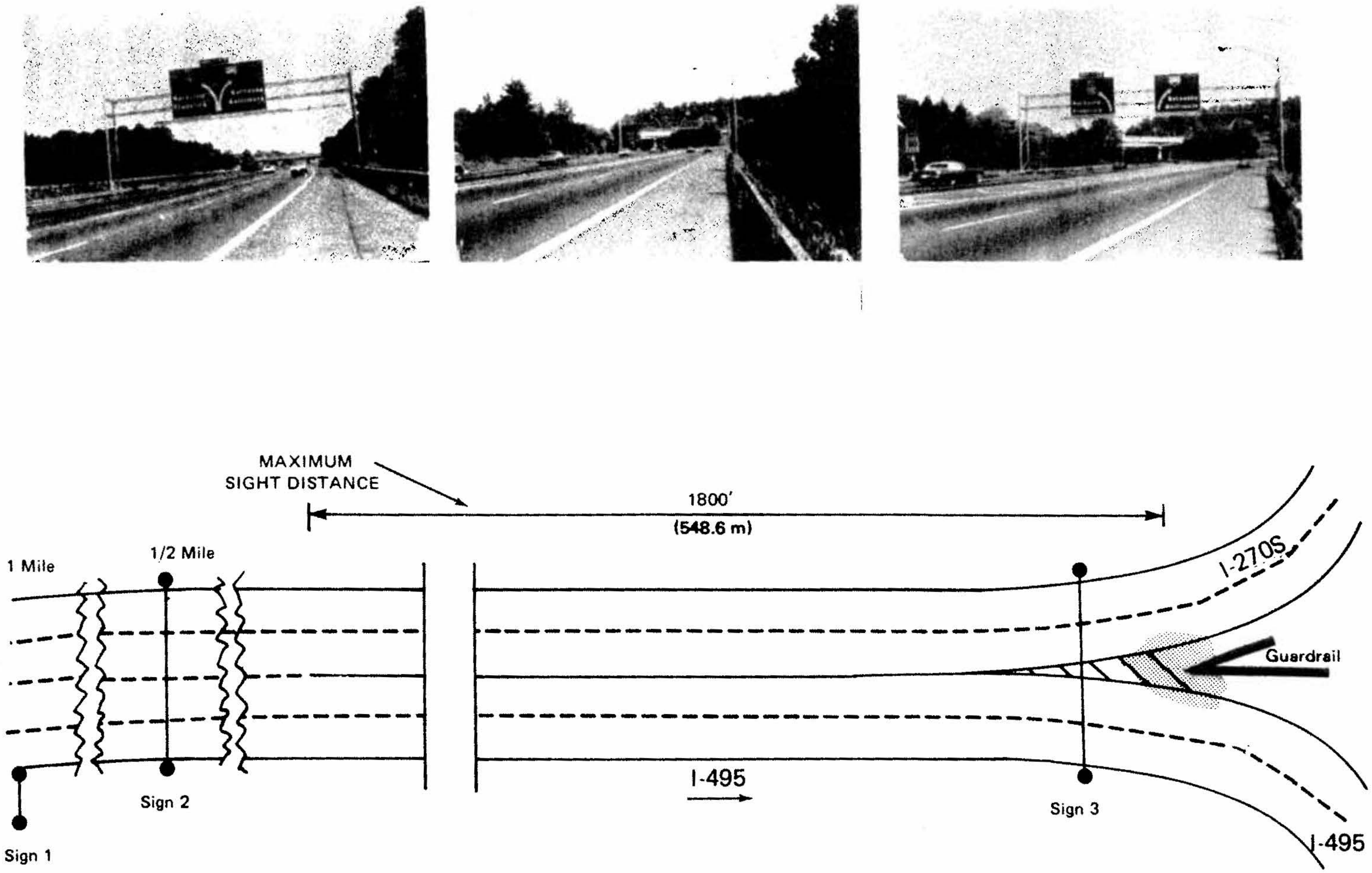


Figure 7. Schematic Illustration of Site #3

Site #4

The fourth site on the test route consists of a right hand exit lane drop at the interchange of I-495 and Maryland Route 355, Wisconsin Avenue (see Figure 8). As can be seen in the diagram, the actual exit ramp and physical gore is just around one of many convoluted portions of this stretch of the roadway. Therefore, the approaching driver is forced to rely on other cues prior to the gore area itself to alert him to the hazard situation and subsequent needs for an avoidance maneuver. This interchange is strongly treated with much advance lane drop signing and delineation, i.e., "RIGHT LANE MUST TURN RIGHT," and arrows pointing to the right painted in the exit lane.

The predetermined reference point chosen, in recognition of the above, was the beginning of the artificial gore and chevron marking. Measured sight distance from this point was 585 feet (128.3 m), which is considerably shorter than the recommended decision sight distance of 725 – 900 feet (213.4 – 274.3 m) for an operating speed of 50 mph (80.5 km/h).

Each subject's task was simply to recognize the hazard and make a lane change to the left so as not to exit from I-495. All responded safely and efficiently to this requirement. However, the responses were to cues which were some distance before the measured sight distance point (artificial gore). In all cases it was obvious that earlier cues alerted the driver to shift left. In fact, one-third responded to the solid white line to the left, one-third to the painted arrows, and one-third to some combination of these two. It seems clear that these types of cues connote the meaning that the lane will drop off and that some adjustment must be made.

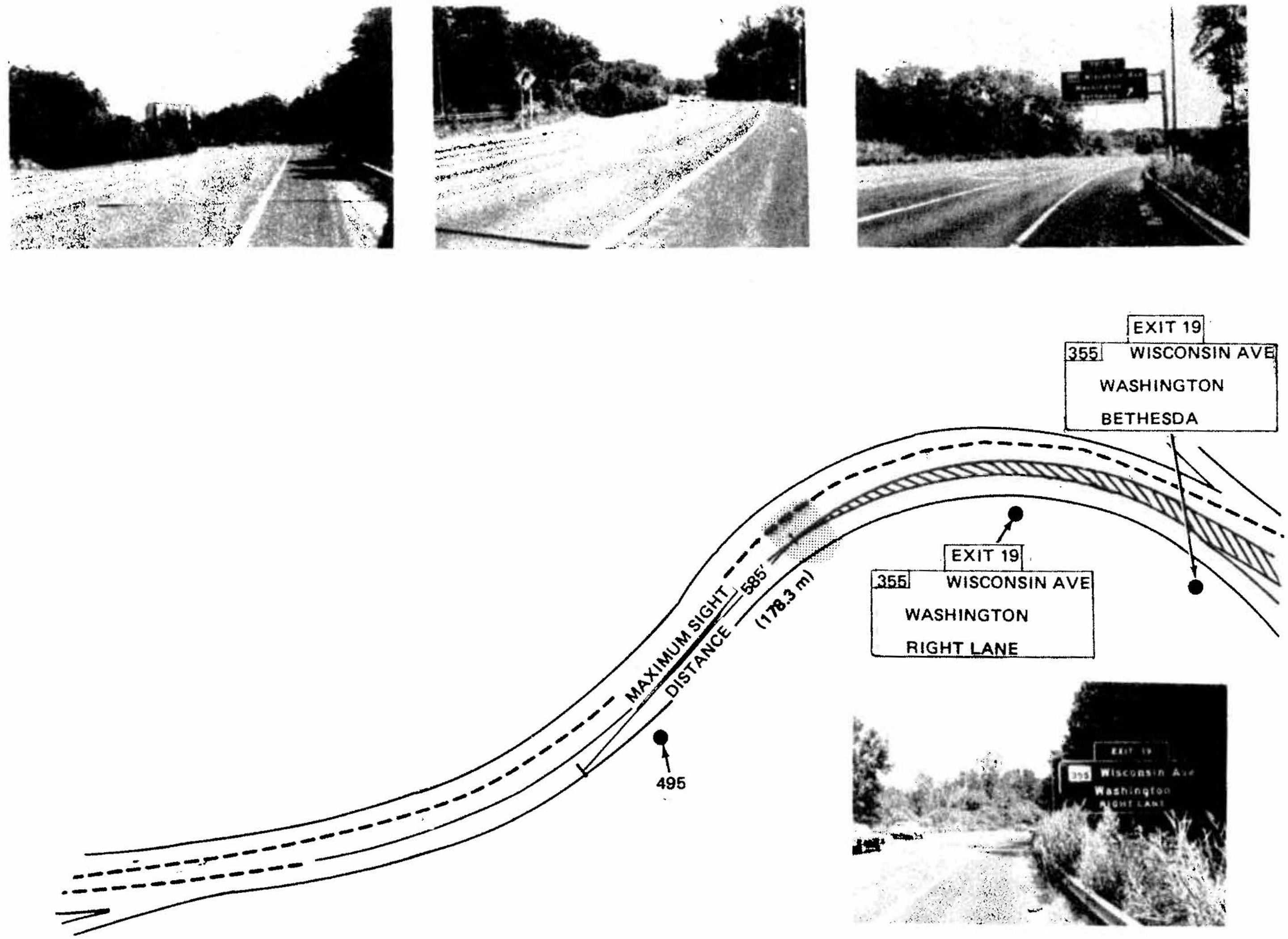


Figure 8. Schematic Illustration of Site #4

Site #5

Site number five is another example of a right hand exit lane drop. It occurs at the interchange of Northbound I-270 and Montrose Road near Rockville, Maryland. This particular lane drop is similar in characteristics to site number one. In this site, however, the beginning of the artificial gore delineation is somewhat truncated, although this is compensated for by a painted arrow in the exit lane, reinforced by two overhead "EXIT ONLY" guide signs (see Figure 9).

The hazard chosen to record maximum sight distance was the physical gore, from which a distance of 1,130 feet (344.4 m) was measured. For speeds of 55 mph (88.5 km/h), this sight distance should have been adequate under the decision sight distance criteria.

None of the subjects failed to safely and efficiently change from the exit lane into the left through lane. However, simple lane change maneuvers were often impaired due to the large volume of truck traffic on this facility. Subjects reported responding to the solid white line or the painted arrow in the exit lane instead of the gore. It seems that these were their first clues to the lane drop and the need to change lanes. The truck traffic, though, influenced their sighting of these cues and subsequent maneuvering such that they still pressed the horn button past the sight distance marker, as if they were responding to the gore. Only two subjects were actually able to respond to these early cues in advance of the marker, although it is assumed that more would have had not trucks blocked their view until the last minute. The popular responses were, as in previous sites, the solid white line and the arrow. Only three subjects were able to, and did, relate their first recognition of a hazard to items on or associated with the gore. Even though truck traffic was a problem at this site, the exit lane itself is long enough to compensate for vehicles obstructing the path.

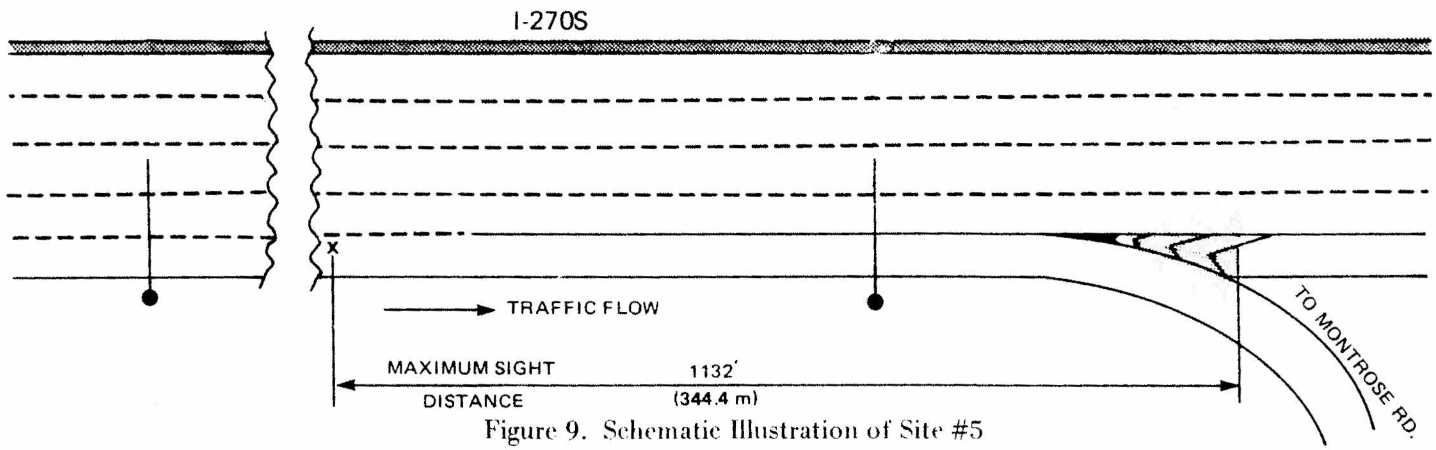


Figure 9. Schematic Illustration of Site #5

Site #6

This site is the first of two urban arterial locations. It consists of a required lane shift to the left while traveling through Rockville on Maryland Route 28 East. As 28 East intersects Maryland Route 355, traffic is channeled into a single lane on the approach to the intersection since the continuation of this facility is a one lane operation beyond the intersection. The channeling is accomplished by physical barricades placed in the right lane just before the intersection (see Figure 10).

The predetermined hazard for this site is, in fact, the barricades themselves. Measured maximum sight distance to the reference point upstream was 3000 feet (91.4 m). At an approach speed of 30 mph (48.3 km/h), this sight distance is inadequate under the decision sight distance criteria.

The required maneuver was to shift left to avoid the barricades so that the subject could continue east on Route 28. Several problems were encountered in successfully executing this maneuver. As opposed to the somewhat controlled, flowing conditions of the freeway sites, this site is encumbered by highly variable traffic conditions and maneuvering time irregularities due to entrapment by the traffic light. Negotiation of the barricade situation proved overwhelming for 27% of the subjects, who missed the lane change and exited off to the right onto Route 355. Others realized the necessity to cut over at the very last instant and simply stopped completely until traffic cleared enough so that they might enter the left lane.

The density of traffic at this intersection was more often than not at a level of service "C" and "D" so that other vehicles both cued and interfered with the subject in his task of finding his way into the proper lane. Trucks were encountered at this site and they appeared to distract the drivers, intimidating them into an improper path so that the intersection was not negotiated properly. In spite of the many difficulties that drivers experienced at this site, almost all reported sighting the barricades as a very definite hazard.

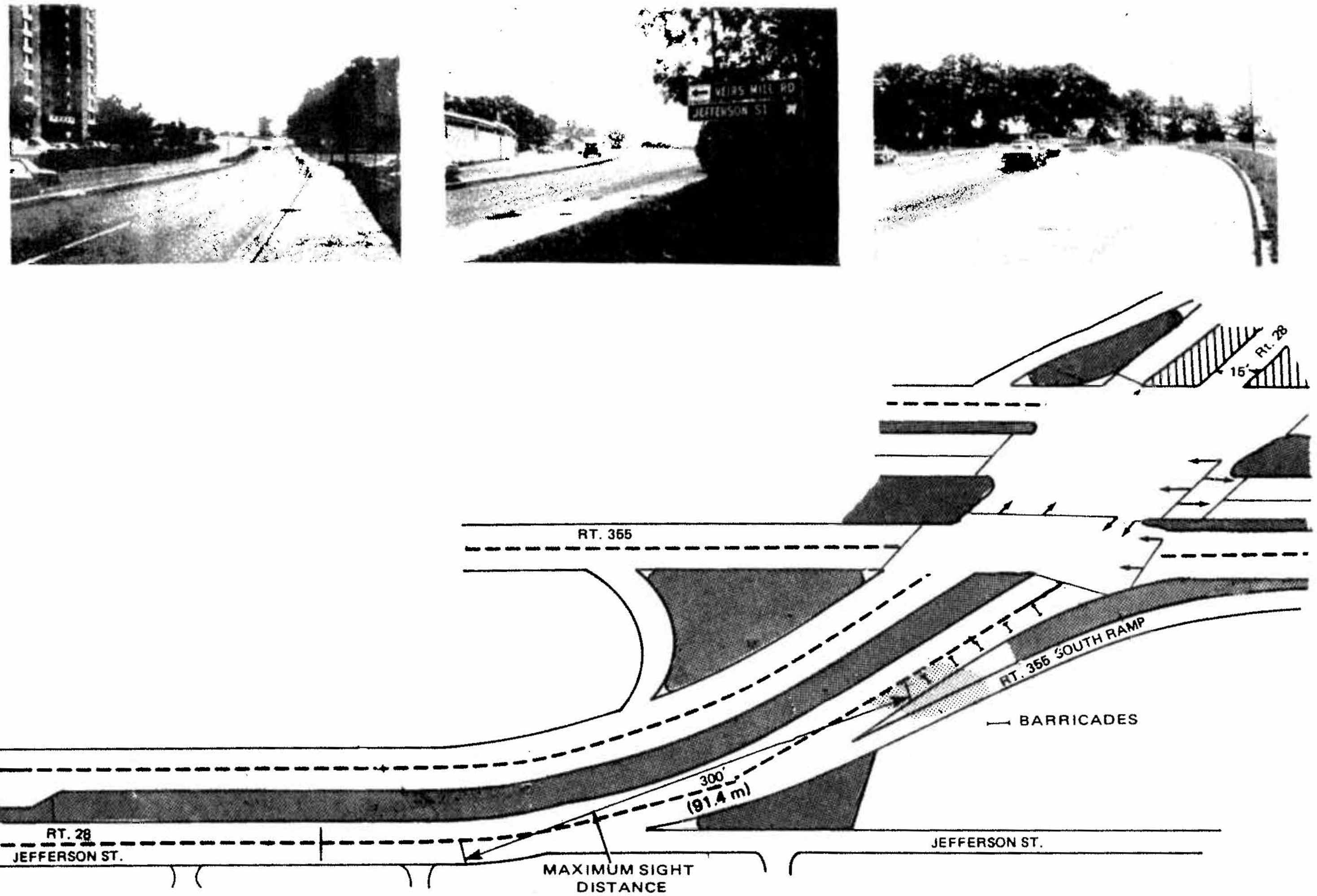


Figure 10. Schematic Illustration of Site #6

Site #7

Site seven is the second of the two urban arterial sites. It is a renegotiation of the intersection encountered in site six, but in this case the driver approaches the intersection from the north, following Maryland Route 355. His task is to pick up Route 28 East as if, again, passing through Rockville. The successful completion of this task requires the subject to shift over to the left lane in two steps: first, to avoid continuation of 355 to the right, and a second shift to avoid barricades in the next right lane. Barricades serve a channeling purpose at this approach to the intersection just as in the approach situation from 28 East in site six (see Figure 11).

Maximum sight distance was measured at 420 feet (128.0 m) from the physical gore separating the left lanes from the through lanes. With an approach speed of approximately 30 mph (48.3 km/h), drivers should have had a decision sight distance of at least 450 feet (137.2 m) (as shown in Table 1).

As in site six, various difficulties were encountered by drivers in negotiating this site. The task included a search of a wide array of visual clutter in order to continue on the test course. Since nearly all of the test subjects were unfamiliar with Rockville and the course they were to follow, they had no alternative but to seek out the 28 East route marker as a cue to reach their destination. This, combined with a degraded decision sight distance, compounded by aggravatingly high traffic density and vehicular interferences, produced a situation wherein response times were generally very high.

Over half (63%) reported sighting the route marker as their first cue to change lanes to the left. Three could not even pick this out among other guide signs in the visual field, and exited off to the right. Of these, two reported responding to the marker for 28 *West*! Some were so caught up in navigational difficulties that they responded in advance of the sight distance marker (18%), and one even took the route marker to mandate a sharp 90° angle turn to the left, thus exiting off of the course. Longer total response times are also attributable to some slight training effects from the previous site, number six. Once the subject realized that the proper continuation of the course required shifting into the left lane to pick up Route 28 East, subjects seemed content to wait for an acceptable gap in the line of traffic in order to make the shift. In all cases, the barricades were an after-the-fact phenomenon, in that the subjects mentioned their presence and hazard status after they had already begun to make corrections in their lane position. It is imperative to reiterate the interactive effects of the congested roadway conditions uniformly prevalent at this site. Not only were drivers subject to problems of traffic density, in one case a construction crew neatly placed a flagperson directly at a crucial spot near the gore which cued this driver off to the left. Naturally, this provided a cue with very high target value from much further upstream than the measured maximum sight distance point. For one or a combination of the above reasons, 59% of subjects failed to negotiate the site in a proper way.

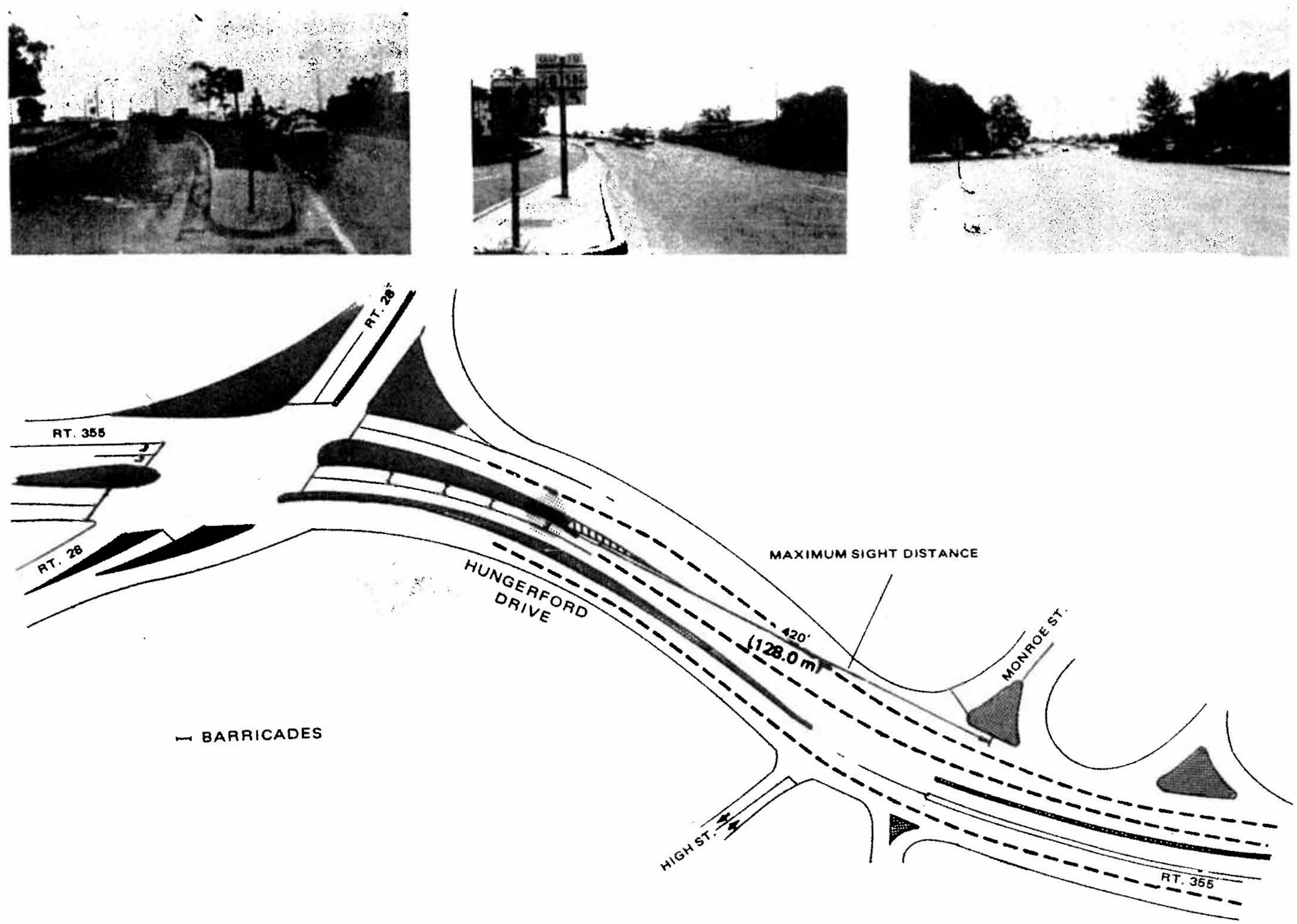


Figure 11. Schematic Illustration of Site #7

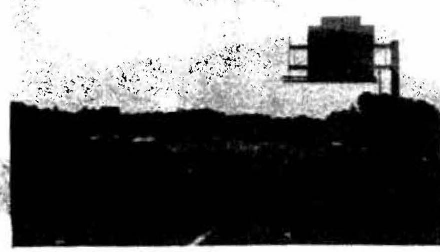
Site #8

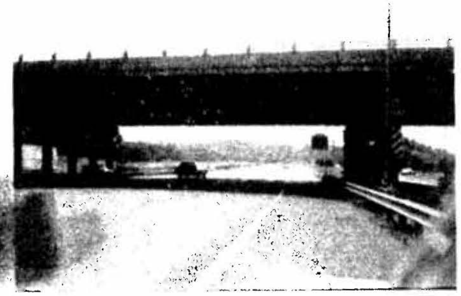
The final site on the test route is a standard right hand freeway exit lane drop, occurring at the interchange of I-495 and the second River Road off-ramp. The exit lane is straightforward and very similar in characteristics to sites one and five. Three unique points distinguish this site, however. First, the approach guide signing consists of two diagrammatic displays, which are very easy to fail to assimilate. Second, an "EXIT ONLY" overhead sign is well hidden until the last instant by the bridge immediately before the exit ramp. Consequently, the driver is fairly well devoid of guide sign assistance to confound his responses. Third, the white solid lines delineating the gore and extending up a short way along the exit lane are very faint and difficult to see (see Figure 12).

In light of the above three characteristics, the pre-determined hazard was felt to be the gore itself. Maximum sight distance from this point was measured at 2,070 feet (630.9 m). At an approach speed averaging 55 mph (88.5 km/h), this distance is well above that necessary to serve the driver.

Many drivers lost the benefit of the extra long sight distance because of the lack of early cues to alert them to the lane drop. Over one-third did not realize that they were even in an exit lane and violated the gore and drove on the shoulder for a time. At this point, drivers recognized the different complexion of a shoulder from an ordinary traveling lane, and then maneuvered over. Many subjects who made this error were so shaken by their realization that they failed to press the horn button at all (25%). The two-thirds who did achieve the proper lane change without violating the gore stated that their cue was indeed the actual gore, as hoped.

Three subjects responded well in advance of the sight distance markers, a reaction in direct contradiction to the majority of responses. This is easily explained, however, since these drivers reported seeing other drivers ahead of them making erratic maneuvers, and thus the test subjects were cued to the lane drop.





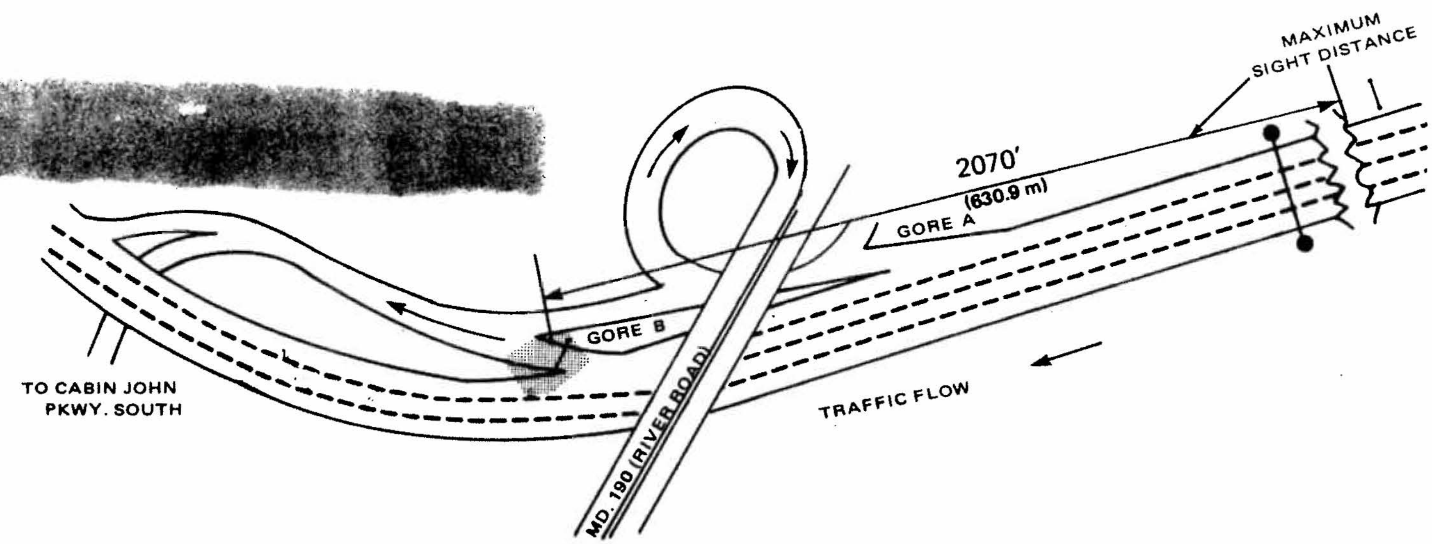


Figure 12. Schematic Illustration of Site #8

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