Human Factors Associated with Interchange Design Features

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Interchanges are freeway design features that pose considerable safety and operational problems for drivers. Most freeway accidents and directional uncertainty occur in the vicinity of interchanges. Reasons for this phenomenon include friction between entering and exiting traffic, variability in design, and a high probability for driver error, the primary contributing factor of accidents. An introduction of general human factors considerations in highway design is presented; it is intended for highway engineers unfamiliar with the science of human factors. Examined are human factors issues associated with interchange design features, including driving task performance, driver error sources, reception of visually displayed information, information handling, driver attributes, sight distance, driver expectancy violations, and information presentation techniques and principles. Key human factors considerations in intersection design and operations are discussed.

Modern freeway design has resulted in safe and efficient travel that is unprecedented. A prime example is the Interstate system. Of the more than 4 million mi of highways in the United States, 45,000 are Interstate highway miles. These freeways carry approximately 22 percent of the more than 1.4 trillion annual vehicle miles traveled with a fatality rate of 1.03 per 100 million vehicle-mi (*1*). Problems on freeways are most likely to occur at interchanges (*2*). Among the reasons for this are (a) the friction that occurs at interchanges between entering and exiting traffic, (b) the high task demand of interchanges, and (c) the greater likelihood of driver error, the primary contributing factor of accidents. The purpose of this paper is to examine human factors issues associated with interchange design features.

HUMAN FACTORS CONSIDERATIONS

The human factors discipline links engineering (e.g., civil and traffic engineering) with behavioral science (e.g., psychology and physiology). It enables engineers to design and operate systems that are compatible with user characteristics, abilities, and limitations. In highway transportation, human factors help to determine driver characteristics and interfaces and gauge the effects of their interaction with traffic, the roadway, its information system, and the environment. Ultimately, human factors considerations are used to develop driver performance-related design and operational standards.

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An appreciation of interchange-related human factors considerations is essential for design, operations, and safety. Engineers should have an understanding of drivers, their characteristics, and their performance. This will help them to optimize interchange designs, information displays, and operational procedures that contribute to driver error. It will enable them to match user characteristics with systems requirements and will allow them to accommodate a diverse and aging population.

DRIVING TASK PERFORMANCE

Human factors considerations of interchange design features should be viewed in the context of the driving task, which consists of three broad levels: control, guidance, and navigation. The complexity of information handling increases with each level. Control involves the driver's interaction with the vehicle and its controls and displays. Guidance involves the maintenance of a safe speed and path relative to the roadway and traffic. Pretrip navigation includes trip planning and route selection; in-trip navigation includes route following and direction finding (*3*).

Proper driving task performance generally results in the safe and efficient negotiation of the interchange, whereas driver error often leads to accidents and inefficient operations such as erratic maneuvers and missed exits. At interchanges, navigation tasks require directional decisions pertaining to the selection of paths to take to follow a route contained in a trip plan or selected in transit. Guidance tasks are predicated on the navigational decision (i.e., to take the interchange or stay on the mainline). They include speed and path decisions in response to the geometric design, performance of the requisite maneuvers safely and efficiently, and maintenance of an area of safe travel with vehicles in the traffic stream. Of primary importance is that drivers must perform guidance and navigation tasks in close proximity, which increases the chances of drivers becoming overloaded or committing errors (*4*).

The key to successful task performance at interchanges is efficient visual information gathering and error-free processing. Given that drivers have to perform multiple tasks often under extreme time pressures, information needs across all task levels must be satisfied. These needs should be satisfied through designs that do not violate driver expectancies or require demanding or unusual maneuvers and through traffic control devices that provide information when needed, where it can be used, and in a form most suitable to the demands of the situation (*5*).

DRIVER ERROR

Driver error is the principal contributing factor in most accidents and many instances of inefficient traffic operations. Errors can occur for a variety of reasons associated with driver physical or mental states and disabilities, task demands, and deficiencies in the design or operation of the highway (*6–8*).

Some driver errors are caused by alcohol or drug use, fatigue, inattention, lack of training or skills, lack of literacy, and such innate sensory-motor deficiencies as poor vision or hearing. There is little that engineers can do to eliminate those problems, which relate to licensing, education and training, and enforcement. In cases in which errors are committed because of the nature of the task, the demands of the situation, lack of visibility of the interchange, expectancy violations, or deficiencies in information display, the error sources can be eliminated. The information display can be enhanced, and the safety and operations of the interchange can be improved. Engineers can ameliorate the following interchange error sources:

- Excessive task demands;
- Unusual maneuvers or task requirements;
- Poor forward sight distance;
- Expectancy violations;
- Too much processing demand;
- Too little processing demand;
- Deficient, ambiguous, confusing, or missing displays;
- Misplaced, blocked, or obscured displays; and
- Small, illegible, or inconspicuous displays.

RECEPTION OF VISUALLY DISPLAYED INFORMATION

Vision is the most important sensory input channel. More than 90 percent of all information is received visually (*9*). A discussion of all pertinent visual reception factors associated with the receipt of information at an interchange is beyond the scope of this paper. However, the following important vision-related considerations should be taken into account in interchange design and operations.

Drivers must have the capability (e.g., visual acuity, color vision, etc.) to receive the information. The visual channel is selective. For interchange information to be received, it must be looked at and attended to. The interchange and its information displays must be within the driver's field of view and cone of clear vision at the freeway's operational speed.

Displayed information must be properly located. There must be sufficient sight distance. This includes both the sight distance to the interchange's design and its associated information treatments (signs, marking, delineation, etc.). The interchange information treatment must possess the physical characteristics (e.g., brightness, color, size, shape, contrast) necessary to be received and used in sufficient time to perform the requisite maneuver(s) safely and efficiently.

INFORMATION HANDLING

Driving is an information-decision-action task. Drivers gather information from sources internal and external to the vehicle and use it with information they bring to the task (knowledge, skills, expectancies, trip plans) to make decisions and perform control actions. In transit, drivers often have to do many things at one time. They generally have overlapping information needs associated with various activities. To satisfy these needs, they search the environment, detect information, receive and process it, make decisions, and perform actions using continuous feedback (*10*).

People are serial information processors in that they can handle only one source of visual information at a time. However, while negotiating an interchange, they often have to process a number of pieces of information and perform several activities at the same time. To do this, drivers juggle information sources and driving activities. They integrate activities and maintain an appreciation of a dynamic, constantly changing environment by sampling information in short glances and shifting attention from source to source. They rely on judgment, estimation, prediction, and memory to fill in the gaps, share tasks, and shed less important information and activities (*11*).

Memory

Drivers constantly handle information, with relevant sources transferred to short-term storage for rapid access, retrieval, and processing. The short-term memory trace lasts from 30 sec to several minutes, with a span of approximately 5 to 9 information sources (*4*). Information in short-term memory that is not relevant, reinforced, repeated, or retrieved and processed is forgotten. Important information may be transferred to the long-term memory, which has no limitations on the amount of information it can store, or on the time frame for retrieval.

Given the short-term memory characteristics, care must be taken to locate upstream information so that it will not be forgotten by the time the interchange is reached. To ensure this may require repetition if the interchange is a major one or if there is a likelihood for events or features to intervene and extinguish the memory trace.

Reaction Time

Reaction time (RT) is the time it takes a driver to receive a piece of information (e.g., a guide sign), make a decision, (e.g., to take the exit), and take an action (e.g., exit). RT varies from driver to driver and is a function of decision complexity (complex decisions take longer than simple ones) and whether expectancies are violated (*12*). It is easier and faster for drivers to make several simple decisions than one highly complex one, and the long time to process a complex decision takes attention away from other needed information. One way to decrease RT is to use simple, single-decision trailblazers to a destination (e.g., an airplane symbol and an arrow to be followed at each choice point on the route to an airport).

DRIVER ATTRIBUTES AND POPULATIONS

There are more than 160 million licensed drivers in the United States. They encompass a broad spectrum of demographic, physical, and sensory-motor attributes, all of which affect the way they receive and handle information at interchanges. For example, there are differences in sex (more male than female drivers), age (from 14 with no experience to over 80 with decreased capabilities), education (from less than high school to college), and training and experience (from novices to experienced drivers to professionals).

Certain driver subpopulations represent a unique segment of the overall population by virtue of their vehicles (e.g., trucks, motorcycles) or their language fluency (e.g., English, Spanish). These subpopulations can affect safety and operational efficiency, particularly when they represent a large portion of the traffic stream or when they require special treatment or information. Problems that occur with trucks negotiating interchanges and the need for special information is an example of this.

There is variability in driver sensory-motor capabilities, with a considerable range in vision, hearing, and reaction time. Most drivers have static visual acuity corrected to 20/40; approximately 8 percent of the male driving population has color vision deficiencies; and the older driving population (65+) experiences some degree of vision and processing impairments that worsen with age (*4*).

Because people age differently, there is no widely accepted age for the definition of "old." Old is usually considered to be 65 years or older. Currently, 15 percent of Americans are 65 or older. Most older drivers retain their licenses and drive daily, although generally not to work and often not at night.

All drivers ultimately experience age-related sensory-motor impairments that vary from driver to driver. These impairments include a gradual loss of vision and information-handling ability. Common problems include poor night vision and glare recovery, decreased visual acuity, increased reaction time, loss of short-term memory, and poor attention span.

Older motorists compensate by driving slower, avoiding stressful situations, and relying on experience. However, they have a higher-than-average accident rate and are often involved in multivehicle collisions at merges, unprotected left turns, and intersections. Because older drivers use freeways more than they have in the past, more consideration of intersection design and information treatments tailored to older driver attributes is required.

Older drivers can be aided by improved sight distance, enhanced signs and markings, better maintenance of traffic control devices, lower speeds, and alternative means of transport. When the percentage of older drivers in the traffic stream is greater than 15 percent, their diminished capabilities should be taken into account by following these recommendations and by designing for the older driver (*13*).

SIGHT DISTANCE

Drivers must have adequate forward sight distance at interchanges, given their overwhelming reliance on vision for driving and their potentially long reaction times for complex decision making. Adequate sight distance provides sufficient time for drivers to gather information, process it, perform the required control actions, factor in the vehicle's response time, and evaluate the appropriateness of their responses in a feedback process.

Stopping Sight Distance

The Green Book (*14*) defines stopping sight distance as "the forward sight distance available such that a vehicle travelling at or near a highway's design speed has sufficient time to stop before reaching a stationary object in its path." It is the sum of the vehicle's braking time and the 2.5 sec brake-reaction time of an average driver, with a seated eye height of 3.5 ft, for a 6-in. fixed object.

Decision Sight Distance

At interchanges, stopping sight distance may not allow sufficient time for an appropriate, unhurried response, since negotiating an interchange has speed, path, and direction changing components and since stopping is generally not an appropriate maneuver. In addition, drivers often have to make complex or multiple decisions, and there may be visual clutter or violation of expectancies. Longer sight distance is needed to provide more time to detect, recognize, and respond to interchanges. More time is also needed to provide a margin for error if a hazard such as a stopped vehicle or a curb is not immediately detected or recognized, or if information is not present, not properly located, or not readily understood.

Decision sight distance provides longer sight distance and hence more time to see and respond. Decision sight distance is defined as "the distance at which a driver can detect a hazard in an environment of visual noise or clutter, recognize it or its threat, select an appropriate speed and path, and perform the required maneuver safely and efficiently." Decision sight distance can be used to determine the adequacy of forward sight distance to the interchange and to position highway information. The interchange treatments in the *Manual on Uniform Traffic Control Devices* (MUTCD) (*15*) generally provide the necessary sight distance. However, some interchanges may require further analysis. In these instances, the procedure contained in the *Users' Guide to Positive Guidance* (*4*) may be used.

EXPECTANCY

Expectancy relates to a driver's readiness to respond to sit- uations, events, and information in predictable and successfu ways. It influences the speed and accuracy of the use of in- formation and is one of the most important human factor considerations in the design and operation of interchange and information treatments.

Configurations, geometric designs, traffic operations, an traffic control devices that are in accordance with or tha reinforce expectancies help drivers respond quickly, effi- ciently, and without error. Configurations, geometric design traffic operations, and traffic control devices that are counte to or violate expectancies lead to longer reaction time, con fusion, inappropriate response, and driver error.

Expectancies operate at all levels of the driving task (*16*) with guidance and navigation expectancies most critical t interchange driving task performance. At the guidance level interchange expectancies relate to highway and interchang design, traffic operations in the vicinity of the interchang hazards that may be encountered, and markings and delineation treatments. At the navigation level, interchange expectancies relate to drivers' trip plans (i.e., what route and destination information they will expect at the interchange), their use of route markers and guide signs, their selection of exits at intersections, how they locate destinations and services. They affect route choice and in-trip route diversion, and ultimately, whether motorists arrive at their destinations with a minimum of inefficiency and confusion.

Two types of expectancies are operative at interchanges. The first are long-term, a priori expectancies that drivers bring to the task on the basis of past experience, upbringing, culture, and learning. The second are short-term, ad hoc expectancies that drivers formulate from site-specific practices, interchange designs, signing and marking treatments, and situations encountered in transit.

A Priori Expectancies

Because everyday objects, systems, and information displays are designed to operate in standard, consistent ways and are applied nationwide, certain expectancies are structured over a lifetime. The intent of consistent, standard interchange designs and information treatments as contained in the Green Book (*14*) and the MUTCD (*15*) is to foster rapid, error-free operations. When standard designs are used, expectancies are reinforced, and performance is rapid and error free. When nonstandard designs and information treatments are used, expectancies are violated, and the driver is surprised. The results may include longer reaction time, confusion, inappropriate response, or an accident. In designing interchanges and information treatments, it is necessary to understand the nature of a priori expectancies. For example, because most freeway exits are on the right, drivers expect all exits to be on the right. Unexpected left exits often have serious consequences. Similarly, in rural areas, drivers often expect all interchanges to be simple diamonds. When a cloverleaf or directional interchange is used, driver expectancies are often violated.

Not all a priori expectancies are held by all drivers, given regional and local differences. Thus, if most interchanges in a given area contain left exits, then drivers in that area would expect to exit on the left rather than the right. This expectancy aids performance in the area familiar to the driver, where interchanges are as expected. However, outside that area, the same driver's response would be inappropriate.

Ad Hoc Expectancies

It is important to recognize and understand the nature of short-term ad hoc expectancies structured by in-transit, site-specific situations. As drivers travel through unfamiliar areas, they form ad hoc, site-specific expectancies on the basis of the geometry of the road, interchange designs, and information treatments. For example, if every interchange on a rural freeway is a diamond with a ground-mounted advance guide sign, an ad hoc expectancy will be structured that similar interchanges will be similarly designed and signed. If a downstream interchange is a cloverleaf and no different advance signing treatment is in place to restructure drivers' expectancies, then the ad hoc expectancy of a diamond would be violated and drivers may not respond properly.

In addition, design consistency should be maintained. If upstream road geometry provides a 70 mph design speed with clear sight lines and adequate decision sight distance to the freeway's interchanges, then strangers will expect these design standards to continue downstream. If downstream design standards are lower, or sight distances reduced, driver expectancies will be violated.

Thus, drivers continuously formulate new, ad hoc expectancies on the basis of what they encounter in transit. Engineers and designers should therefore understand and account for each type of expectancy. Both a priori and ad hoc expectancies should be considered in design and operations. Appropriate expectancies should be reinforced and expectancy violations eliminated through the use of consistent, standardized interchange designs and appropriate uniform information treatments. Consistency should be maintained within and between locations and jurisdictions, and it should be recognized that upstream practices affect downstream expectancies.

INFORMATION PRESENTATION PRINCIPLES AND TECHNIQUES

Any information carrier that assists or directs drivers in making speed or path decisions at interchanges aids the guidance task. Information carriers that provide direction and destination information and assist or direct drivers in making directional decisions at interchanges aid the navigation task. All needed information at interchanges should be presented unequivocally, unambiguously, and conspicuously enough to meet decision sight distance criteria, reinforce appropriate expectancies or restructure expectancies that are violated, and enhance the probability of appropriate speed, path, and directional decisions.

Design for Drivers and Target Populations

Information at an interchange should be presented in nontechnical terms because drivers may not understand engineering concepts. It should also be determined whether there are target groups whose needs must be addressed. These groups may be older drivers with vision problems or truck drivers negotiating sharp ramps.

Be Responsive to Task Demands and Driver Attributes

Highway information should convey the operating conditions of interchanges, be responsive to the task demands imposed on the driver by interchange design and geometry (particularly when there are time pressures caused by traffic), and be sensitive to driver sensory-motor attributes. Drivers may become overloaded when they have to process too many sources of information, or when an information source has too much information content. Overloaded drivers may become confused or miss important information sources.

Satisfy All Information Needs

All information needs relative to all aspects of the driving task at the interchange should be satisfied. Speed and path information should always be available. Information needs pertaining to routes, destinations, directions, and services should be displayed when appropriate. Information should be displayed when needed, where required, and in a form best suited to the driver and task.

Maintain Interchange Design and Information System Compatibility

Because drivers formulate driving strategies on the basis of their perception of the design and operations of an interchange, incompatible information displays will lose credibility and may lead to confusion. A determination should be made on how interchange designs and information treatments appear to drivers and whether they are compatible and do not violate expectancies. In the design stage, models or computer simulations could be used to make this determination and to ensure compatibility.

Avoid Surprises

Driver performance is enhanced when forward sight distance provides a clear, unobstructed view of the interchange, its traffic, and its traffic control devices. Problems often occur when drivers are surprised by unexpected or unseen features. If any aspects of the interchange could surprise drivers, advanced warning should be provided.

Eliminate Information-Related Error Sources

Information-related error sources should be eliminated. These sources include missing information; information obscured by foliage, structures, earth berms, dirt, snow, or the like; misplaced information (not in a driver's field of view); devices too close to a choice point; and obsolete, nonstandard, ambiguous, or confusing messages.

Resolve Conflicts When Information Sources Compete

When information sources compete for a driver's limited processing capacity (generally 5 to 9 sources or 2 to 3 bits of information), or when there is a chance of overload, a determination should be made as to what information sources should be displayed, and which should be spread out, moved, or removed. Generally, guidance information relating to speed and path takes precedence over navigation information relating to direction.

Use Spreading

Spreading reduces the chance for overload at high-processing-demand locations by moving less important information sources upstream or downstream, thereby reducing the processing load.

Use Repetition for Interchange Information Treatments

If a time greater than 30 sec to 2 min, a driver's short-term memory span, intervenes between the receipt of advance interchange information and the exit ramp, drivers may forget the message. Repeating the information one or more times will help drivers remember and act on it. Repetition is also useful if an information display may be blocked by foliage or trucks.

Use All Available Navigation Aids and Treatments

Appropriate navigation aids should be used. These aids include overhead signs that can be seen over trucks, oversized route guidance signs to help drivers at choice points, trailblazers to freeways and interchanges, real-time changeable message signs to warn of incidents and help manage congestion, and highway advisory radio, which transmits information into a road user's vehicle (*4*).

CONCLUSIONS

An interchange is the freeway design and operations feature that is most likely to lead to driver error, accident involvement, and driver directional confusion. Consequently, it is important that the design of an information treatment at an interchange is optimized to maximize driver performance and minimize error. One way to achieve this goal is through the application of human factors principles associated with the design and operational features of an interchange.

A number of human factors considerations should be taken into account in freeway interchange design and operations. These include the sensory-motor attributes of drivers, particularly older drivers (age 65+), the way they perform the driving task, the visual capabilities of the driver, the information-handling attributes of the driver, the reasons for driver errors at interchanges, the importance of adequate interchange sight distance, the role of driver expectancy in interchange design, and factors affecting information treatment at an interchange.

The human factors considerations identified here are all important to the safety and operational efficiency of interchanges. It is therefore concluded that engineers and designers should be aware of and account for all of them and bear in mind that their efforts are first and foremost to aid the driver. In this regard, those human factors considerations associated with driver error involvement, expectancy violations, and sight distance criteria are the most critical.

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