U.S. Department of Transportation (DOT), that is, the National Highway Traffic Safety Administration (NHTSA) or the Federal Highway Administration (FHWA). However, we should not limit our thinking to the kinds of research that they might fund. Research needs may be identified that many appear to be more fundamental than those NHTSA or FHWA has previously been willing to consider. Nevertheless, we should not ignore such research issues if we agree that they are truly essential. On the one hand, we may be able to persuade DOT that they should and could fund such research. Failing that approach, if the research is critical to what we need to know, then we need to look elsewhere for funding. We cannot allow the constraints that have existed in the past to limit what we can do in the future. If we are to be truly competitive in a world market, we are going to have to do some things that will be radical departures from past practices. The field is desperately in need of new and innovative thinking and approaches. If we restrict ourselves to simply doing more of the same, we are, in effect, conceding defeat before we even begin. So, do not limit yourselves to whatever you think might be feasible based on past experience. Instead, remove traditional constraints and focus completely on what you see as the real information needs, be they methodological, theoretical, basic information on decision making, cognition, learning, or whatever else. This is not the time to hold back. Rather, it is an opportunity to plow new ground, fire new gray cells, and kindle new possibilities.

There has never been a more exciting time to be in this field, and there has never been a time when there has been greater awareness and appreciation of the critical need for the participation of this group of experts.

BACKGROUND PAPERS

HIGHWAY ISSUES AND HUMAN FACTORS KNOWLEDGE GAPS FROM THE ENGINEERING PERSPECTIVE

Traffic Operations, Highway Safety, and Human Factors

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INTRODUCTION

Traffic engineering is concerned with the safe and efficient movement of people and goods on streets and highways. Traffic operations is the subset of traffic engineering that establishes the procedures that yield the movement of people and goods. The goal of traffic operations is to make those movements as efficient and safe as possible.

Traffic operations take place on streets and highways; thus there is a direct and important link between highway design and traffic operations. Facilities are designed to operate under specified conditions and within certain constraints. In order to operate, the system must exert some level of control; therefore, traffic control devices (TCDs) become important tools to the operator. The improper use of TCDs can have a serious adverse effect on traffic operations.

Perhaps the most challenging aspect of traffic operations is the human factor. While highway design features and TCDs are fixed or operate within a controlled set of parameters, the range of human (highway user) operating characteristics is enormous, diverse, and constantly changing. In other words, each driver and pedestrian represents a powerful, independently operating "computer" capable of sensing and analyzing information and making decisions. The presence of such power provides a tremendous resource for meeting our mobility demands if it can be directed and coordinated for the collective good of all traffic system users. Such a task is very difficult and complex because these "computers" often have limited communication abilities and skills, a diverse knowledge and understanding of the operating rules, and a unique ability to reason illogically, not to mention the compounding effect of human feelings and emotions.

This paper attempts to explain how the traffic operator currently aspires to the goal of safely and efficiently moving traffic. It also offers some thoughts about areas for further human factors research.

THE TRAFFIC OPERATIONS FRAMEWORK

Traffic operations takes a given highway system, integrates the travel demands placed on that system, and produces a system level of performance reflected by appropriate measures of effectiveness (MOE's). Each component of this simple framework is discussed briefly below.

The Highway System

The driver, vehicle, and roadway have from the earliest days of traffic engineering been the basic components of the highway system. In modern times, we have expanded the definition and description of the traditional trilogy. "Drivers" are now referred to as "users." These users include motor vehicle operators, motorcyclists, bicyclists, pedestrians, and vehicle passengers. They are collectively the human factor with whom the traffic operator must deal and serve.

The term "vehicles" has not changed over the years; however, the characteristics of highway vehicles have changed considerably. For example, automobiles have become smaller, trucks have become larger and heavier, and the engines in both have become more powerful. In the future, we expect our vehicles to be smarter, as Intelligent Vehicle/Highway Systems (IVHS) are developed and implemented.

The term "roadway" has always included not only the road, but also the environment surrounding it. The physical facility consists of lanes, ramps, shoulders, medians, sidewalks, paths, and roadside features, such as barriers, curbs, trees, and poles. It may be straight or curved, flat or hilly. It may be separated from other roads or share space with them at points of crossing. The environment includes the weather, lighting conditions, road surface conditions, and the type of land use adjacent to the facility.

Travel Demand

The principal function of a highway system is to service the travel demand placed on that system. Travel demand is created by "trip generators," i.e., places where people want to go. Trip generators may be categorized simply as home or as places for working, shopping, or recreation. The traffic operator must be able to estimate the impact of existing trip generators and be able to reasonably forecast the impact of future generators. The impacts are specified in terms of how many trips the generator will attract and when those trips will be made.

A second aspect of travel demand is a thorough understanding of the characteristics of the trips taken. Attributes of trip making include trip purpose, type of vehicle, age and experience of user, time period of the trip, distance traveled, and route selected. It is the composite of these characteristics for a particular roadway segment, intersection or network of streets that is of interest to the traffic operator. This composite is reflected as a "traffic pattern" when viewed for specified time periods. Time periods are commonly defined as morning peak, afternoon peak, off-peak, and special event. Traffic operations and controls are implemented in response to the traffic patterns that exist during specified time periods.

System Performance

The bottom line for a highway system is how well it performs in meeting the travel demands placed on it. Users of the system expect safe and convenient mobility free of congestion. That is a tall order for the traffic operator, who must meet that expectation with the system that transportation planners and highway designers have provided. Mobility, safety, and convenience are the goals in traffic operations. To determine how well those goals are achieved, traffic operators rely on MOEs.

The performance of a highway facility is measured against the "capacity" of the facility. Capacity is the maximum rate at which users can reasonably expect to pass a point or section of road under prevailing roadway, traffic, and control conditions. "Level of service" is a qualitative measure that describes operational conditions within a traffic stream and their perception by highway users. The description of operational conditions takes into account such factors as speed, travel time, freedom to maneuver, traffic interruptions, comfort, convenience, and safety. Other MOEs include accidents, delay, and user complaints.

FUNDAMENTALS OF TRAFFIC FLOW

Highway planners, designers, operators, and researchers should have a basic knowledge of traffic flow fundamentals. Important flow characteristics include speed, volume, density, headway, time-space trajectories, and delay. Several important analytical techniques are employed to assist in understanding the complexities of traffic flow. They include supply-and-demand modeling, capacity analysis, traffic stream modeling, shock wave analysis, simulation modeling, and queuing analysis. Traffic flow may be categorized as either uninterrupted or interrupted. These two terms describe the type of facility, not the quality of traffic flow at any given time. Each category is discussed briefly.

Uninterrupted Flow

Traffic conditions on uninterrupted flow facilities result from the interactions among vehicles in the traffic stream and between vehicles and the geometric and environmental characteristics of the facility. There are no fixed elements, like traffic signals or stop signs, to interrupt the flow of traffic. Freeways and highway segments between intersections are considered uninterrupted flow facilities.

The operational state of a traffic stream is defined by three measures: speed, rate of flow, and density. Speed is the rate of motion of vehicles expressed as distance per unit of time, usually miles per hour. The speed measure used for a traffic stream is average travel speed. Rate of flow is a measure of the amount of traffic passing a point in a given time period. The term "volume" is used to mean the actual number of vehicles observed, whereas, "flow rate" is found by taking the number of vehicles observed in a sub-hourly period and dividing it by the time (in hours) over which the vehicles were observed. The common unit for volumes and flow rates is vehicles per hour. Density is defined as the number of vehicles occupying a given length of road averaged over time. The common unit for density is vehicles per mile. It is an important parameter in traffic operations because it reflects the freedom to maneuver within the traffic stream.

The relationship among the parameters speed, flow, and density is fundamental to the theory of uninterrupted flow.

FLOW = SPEED x DENSITY

The general form of the relationships of these parameters one to the other is shown in Figure 1. Note that when there are no vehicles, density and flow are zero. When density increases to the point that all vehicles must stop, flow is also zero. Between these two extremes, a maximizing effect occurs that defines the capacity of the facility. As capacity is approached, available gaps in the traffic stream are fewer, speed declines precipitously, and flow becomes unstable. Unstable conditions exist on the entire high-density, low-speed side of the curves representing forced or breakdown flow. Stable flows exist on the low-density, high-speed side of the curves. The necessity of maintaining traffic operations at or below capacity is graphically illustrated.

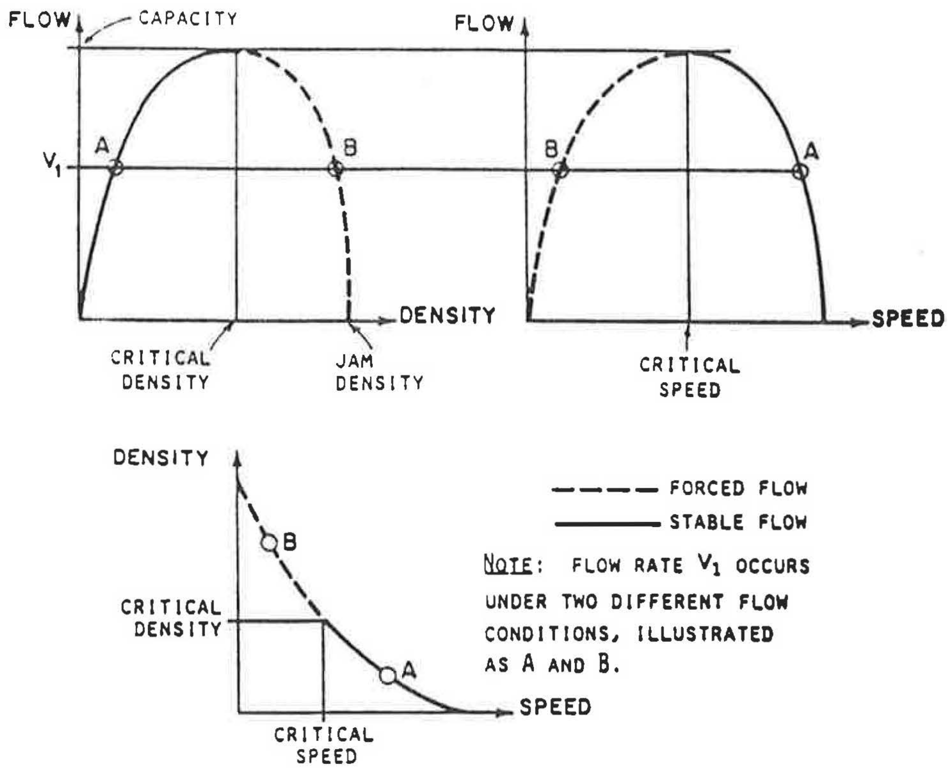

Figure 1. Relationships among speed, density, and rate of flow on uninterrupted flow facilities.

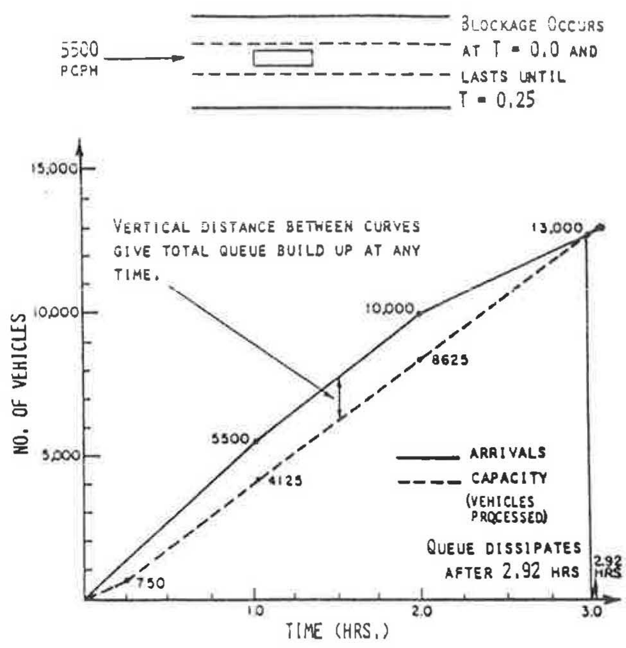

Figure 2. Effects of breakdown illustrated.

Flow breakdowns occur not only when capacity is exceeded by demand volumes but also when constrictions, either permanent or temporary, are encountered on a facility. These "bottlenecks" may be caused by a physical narrowing of the roadway, restrictive curvature, or the occurrence of an "incident," i.e., a disabled vehicle or accident. The impact of blocking one of three lanes on a freeway segment for 15 minutes is illustrated in Figure 2. With the capacity of this segment reduced by at least one-third, the near-capacity demand quickly creates queuing that takes nearly three hours to dissipate.

Interrupted Flow

Fixed elements that cause periodic interruptions to traffic flow characterize interrupted flow facilities. These elements are usually in the form of traffic signals, stop signs, or yield signs. Facilities classed as interrupted flow include signalized and unsignalized intersections, arterials with signals spaced less than two miles apart, and pedestrian and transit flows. These facilities operate by allowing the users to share time and space. Interrupted flow is far more complicated than uninterrupted flow. The traffic operator must ensure that conflicting movements are avoided and at the same time maintain a reasonable level of efficiency. Traffic control devices are the primary tools used to this end. Traffic signals are the most restrictive of these devices, yet provide the most positive form of control. Advances in traffic signal control techniques and equipment, when properly deployed, have increased the responsiveness of the signals to actual traffic demands, thus raising the efficiency of operations at the intersection.

Since flow in each movement or set of nonconflicting movements is halted periodically, attention is focused on the amount of "effective green" time that can be safely provided. Ideally, we would like vehicles to move through the intersection in a stable moving queue with uniform headways from the beginning to the end of the displayed green for that movement. Such a rate of flow for one hour of uninterrupted green time is known as the "saturation flow rate." The headway at this flow rate is called the saturation headway.

In reality, flow in any movement is halted periodically and must therefore start up again. The first driver in the queue must observe and react to the signal's changing to green, release the brake, and accelerate through the intersection. This reaction and acceleration

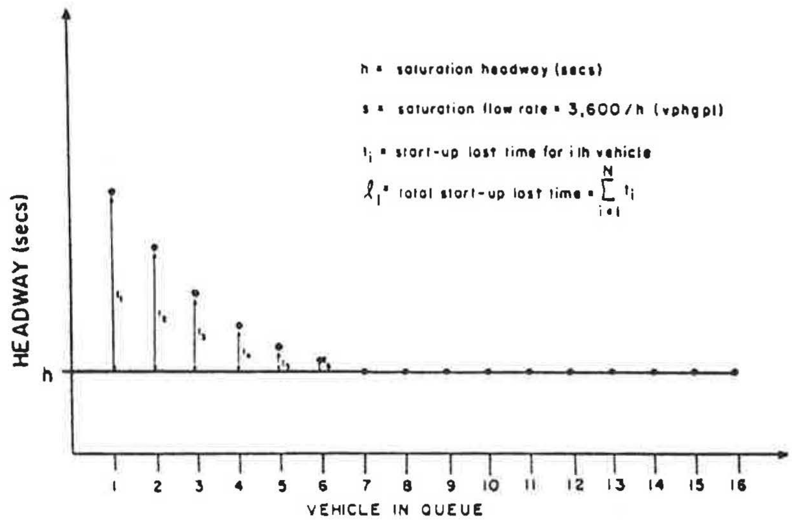

Figure 3. Saturated flow rate and lost time.

time is longer than the saturation headway. The second driver follows the same procedure, but part of his or her reaction and acceleration time occurs simultaneously with that of the first driver, so it is a bit shorter. Similarly, the rest of the queue follows suit until vehicles are once again moving through the intersection at saturation headways. Field observations show that saturation headways are usually reached after the sixth vehicle on average. The time spent getting the queue under way is known as "start-up lost time" and is depicted graphically in Figure 3.

Time is also lost when a stream of vehicles is stopped. Safety requires that some clearance time be allowed before a conflicting movement is released. Although in practice drivers use part of the displayed clearance interval, they rarely use it all. The unused portion of the clearance interval is known as "clearance lost time." Therefore, "effective green" is the displayed green plus clearance interval minus the sum of the lost time.

The amount of lost time obviously affects capacity. Each time a movement is stopped, lost time is incurred and capacity is reduced. Increasing the cycle length, and thus the time between stops, increases capacity up to a point. Other factors, such as overflowing left-turn storage lanes that block through lanes, enter the picture. Average stopped-time delay per vehicle tends to increase when cycle length is increased, and saturation headway has been observed to increase when the continuous greens have become too long.

At unsignalized intersections, the key ingredient to safe and efficient operations is driver judgment in the proper section of a gap to enter the traffic stream or cross the intersection. Gap acceptance characteristics depend on the type of maneuver to be executed, the width of the street to be crossed, the speed of approaching traffic, sight distances, time waiting, and the individual physical abilities of the driver.

TRAFFIC OPERATIONS TOOLS

Highway mobility and safety are a function of how well we manage four elements of the transportation system. Those elements are supply, demand, land use, and the institutional and funding framework. Traffic operations is certainly affected by land use, funding, and institutional constraints. However, the traffic engineer is principally in the supply-and-demand end of the business; supply deals with providing more capacity, while demand centers on reducing the numbers of vehicles in the system during periods of congestion. A number of tools are available to assist the traffic operator in these tasks.

Tools To Increase Capacity

The most obvious ways to increase capacity are to build more roads, to make the existing roads bigger, or both. In other words, the physical space is increased so that more vehicles can be accommodated. This solution has been used extensively in the United States. It will continue to be used in the future but to a lesser degree. First, it is very expensive. Second, we are running out of space on which to build or expand.

In cases where building new roads or improving existing roads is possible, care must be taken to provide adequate geometric design to meet the needs of both present and future user populations. Our population is aging and attention must be focused on providing future roads and road improvements for future users. Safety during construction has drawn a lot of attention since the mid-70's and continues to require vigilance in providing well-marked, safe paths through work zones. Access control and management are critical on future roads. Mobility and access are competing entities, whereas increasing one decreases the other, and vice versa. A clear statement of the purpose for a facility should lead to the appropriate mix of mobility and access.

Because of our seeming inability to manage growth and the increasing physical and funding constraints facing new road building, attention has turned to traffic management. How can we get more capacity out of existing systems? For many years, a number of techniques have been used to increase capacity and flow on streets and highways. We have provided or designated special lanes on urban freeways for high occupancy vehicles or trucks only. Freeway surveillance has been used on many of our systems. Ramp metering has improved flow on freeways by controlling the input of traffic into the traffic stream so that turbulence is reduced at on-ramps. Motorist information systems in the form of changeable message signs and radio broadcasts have been used to inform drivers of conditions on the freeway to aid the drivers in choosing times and routes for their trips. On arterial and local streets, we have used intersection geometric improvements, turn prohibitions, one-way streets, reversible lanes, improved traffic control devices, parking management, traffic signal improvements, and goods movement management.

More recently, we have instituted improved freeway surveillance and control systems and integrated incident management systems with them to speed up detection, response, and removal of disabled vehicles and accidents. On some freeway facilities, lanes are being added by restriping without widening the freeway. Computerized signal systems are being used increasingly on arterials and street networks. Arterial surveillance and management are being used in a few areas. Traffic signal controllers and vehicle detection devices are becoming more sophisticated and efficient. Efforts are being made to improve transit operations. Left-turning traffic has always posed a challenge to efficient operation of an intersection. Some cities are now using dual left-turn lanes to better handle heavy turning movements.

While traffic management strategies and techniques usually result in improved flow, the infrastructure must be maintained in a serviceable condition if sustained increases in capacity are to be realized. So, while physical facility expansion is decreasing, the need for maintenance is increasing. And as traffic control becomes more sophisticated, it must be designed so that people will accept, understand, and respond to the devices and techniques in a way that results in meeting the users' needs for safety, mobility, comfort, and convenience.

Tools To Control Demand

The other side of increasing supply is reducing demand. There are three ways to approach reducing demand. The first is to reduce the magnitude of the demand. We commonly measure travel demand in terms of some combination of number of trips and trip length and express it as person miles (or vehicle miles) traveled. Shorter work weeks, shorter average trip lengths, and more work at home are ways that reduce overall travel demand. The shorter work week implies a longer work day, which tends to shift the demand pattern on work days. Even if everyone traveled one day a week less, there would still be one or more days when everyone traveled to work; thus the "design" demand may not change. This approach might work better when applied in combination with some of the other approaches.

Shorter work trips occur when the worker and the job site are located closer to one another. The movement of jobs from large cities to smaller decentralized locations has generally reduced trip lengths. The efforts of workers to seek homes closer to their workplace and shopping have also reduced trip lengths. The great movement to the suburbs that has occurred over the past 30 years has changed the pattern of commuter travel. Suburb-to-suburb travel is now twice that of the traditional suburb-to-center city travel. If suburb-to-suburb trips are shorter than the old Central Business

District (CBD) trips, we are reducing demand. If not, the problem continues to grow.

The idea of working at home through the advent of telecommunications is still not a reality. Less than one percent of the work force actually works at home. The larger impact that tele-communications has had on travel is the decentralization of businesses, one reason for the movement of jobs from the central city to the suburbs.

A second approach to reducing demand is to repackage it. This is accomplished by encouraging higher vehicle occupancies and by increasing transit ridership. In short, more people are put into fewer vehicles. Techniques have included high-occupancy-vehicle lanes and programs to encourage carpooling, vanpooling lots park-and-ride lots, express buses, and transit rider incentives. Restricted parking and automobile access are being employed in some areas. Congestion-road pricing is being explored to increase ridesharing and transit use.

The third approach to reducing demand is to shift the temporal distribution of the demand. In most congested areas, the problem is too much demand for given periods of the day, the "peak periods." If the peak periods could be spread out over a longer time, there would be less demand on the system at any given time. This shifting can be accomplished by staggered work hour and variable work hour programs. In recent years, we have seen many businesses provide flex-time or extend their operating hours outside the traditional work-day hours. Even if businesses are willing to adopt these programs, it is very difficult to coordinate among workplaces to gain efficiency in spreading the demand. These methods for shifting demand may be more effective when combined with shorter work weeks.

INTELLIGENT VEHICLE/HIGHWAY SYSTEMS

Much attention has been focused recently on high-technology communications and computing systems applications to moving traffic safely and more efficiently. Smart cars operating on smart highways offers potential relief from the problems of urban congestion. While optimism abounds about the potential of IVHS, the extent of the actual impact has yet to be determined. However, IVHS offers a promising approach to developing devices and techniques that will aid the traffic operator in the quest to increase capacity and reduce demand.

There is much that technology may be able to do to make vehicles safer and to better enable drivers to avoid accidents. Examples of these technologies include radar braking, in-vehicle navigation, night vision enhancement, heads-up displays, and even longitudinal and lateral vehicle control.

Outside the vehicle we envision advanced traffic management and traveler information systems. Research is under way to develop and test integrated freeway and arterial network surveillance and control systems. The use of "probe" vehicles in the traffic stream could provide traffic condition information to traffic control centers and allow for more responsive or even predictive traffic control patterns to be used as needed. Real-time information systems would alert travelers at home or work or in their vehicles to traffic conditions on their intended routes with advice on how best to avoid delays. In the distant future, we may even see automated highways that allow close headways at high speeds.

HUMAN FACTORS RESEARCH ISSUES

Whatever the future may hold, there are many human factors issues in the field of traffic operations that need attention. While IVHS constitutes a major subject for human factors and the interface required between people and these systems, there are many questions yet to be answered about the effective and efficient use of many of our present-day traffic operations techniques. The following is a listing of some of these questions. They are in no particular order as to importance.

1. Driver Attention in Congested Traffic Situations. As traffic flow nears capacity and vehicles move closer together, drivers are required to increase their vigilance and pay closer attention to conditions around them. How can this level of awareness be achieved and maintained? What is the driver's learning curve as he or she becomes acclimated to congested conditions?
2. Rubbernecking. Incidents in the form of breakdowns or accidents cause delays to traffic moving in the direction of lanes that are blocked or restricted. These situations are handled by quick response and removal of the incident. The part of the problem that is not being addressed concerns the slowing down of traffic moving in the opposite direction where no blockage or lane restriction exists, i.e., rubbernecking. People are curious and want to see what happened. In some cases, the distraction of the incident has resulted in an accident on the free-flowing side of the highway. How can this natural curiosity be satisfied without disrupting the smooth flow of traffic past an incident?

3. Turning Movements at Intersections. The execution of a turning movement at an intersection can be a complex and taxing maneuver for many drivers, particularly older drivers. Several aspects of executing turning movements deserve attention. At multilane signalized intersections where turning movements are protected by the signal phase, the proper selection of the lane to turn into is a problem for many drivers. This problem is compounded at intersections with dual left-turns. Older drivers seem to have difficulty executing a turning maneuver alongside another vehicle. Drivers of all ages exhibit difficulty with maintaining the proper lane upon completing the turn. At intersections unprotected by signals, drivers misjudge the speed of oncoming vehicles when executing their turns. How can turning movements at intersections be made safer?
4. Car-Following Behavior. The traffic operator seeks smoothness of flow in the traffic stream. Reliance is placed on drivers to adjust their speed and following distance to suit prevailing conditions and situations. How can drivers better learn and be motivated to execute safe following distances and speeds?
5. The Impacts of IVHS Technologies on Highway Users. Almost every conceived technique requires interface with the users. Many systems are designed to reduce the information load on the driver. Other systems may result in overloading or distracting the driver with information. Traffic control systems external to the vehicle must be understood by users so that they can make decisions that will enhance the operation of the total system. How can human factors involvement in the design and operation of IVHS systems alleviate these problems?

SUMMARY

Traffic operations, highway design, traffic control devices, safety and human factors are intricately linked. The safe and efficient operation of our highway systems requires that these components be fully integrated and mutually supportive. We must seek ways to build our systems so that they take advantage of the collective mental power of the systems users and serve the mobility needs of our society.

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Traffic Control Devices, Highway Safety, and Human Factors

Dr. Robert Dewar, Western Ergonomics, Inc.

INTRODUCTION

The control of roadway traffic is essential to the safe and efficient movement of vehicles and pedestrians. It traditionally has been the domain of the traffic engineer, but human factors has come to play an increasing part in the design and use of traffic control devices (TCDs) over the past three decades. The need to know about drivers' limitations in information processing and behavior as these relate to traffic control will be examined, a brief review of some relevant literature presented, and future research needs identified.

The driving task can be broken down into three main components: control (driver interaction with the vehicle in terms of speed and direction), guidance (maintenance of a safe speed and path by keeping the vehicle in the proper place in the lane), and navigation (executing a trip from one location to another). Much of the driver information necessary for the last two of these comes from TCDs. This way of looking at the driving task is the basis for the positive guidance approach (Alexander and Lunenfeld 1975).

Several criteria must be met for a TCD to be effective. Initially, it must command attention or be easily detected by the person who needs the information. It must be legible at the appropriate distance (in time to take the necessary action) and must often be legible when seen for a very brief time - glance legibility. At busy urban locations, TCDs can easily be hidden by large vehicles and seen only briefly. The device should also be quickly understood, as drivers often have only a second or two to interpret and respond to the message.

The relative importance of these various design criteria has never been established. They are not all of equal