duction to about 25 km/h (16 mph) can raise gap acceptance—and capacity—at rotaries and elsewhere.

A road has been cut through the center of several circles in the Washington, D.C., area. The circle then no longer operates on the rotary principle, which requires that all entering drivers yield. It functions in a manner similar to two jug handles and needs signals.

Finally, like Leisch, I am interested in the philosophy of traffic control. Since the profession has for 50 years advocated the use, wherever possible, of controls less restrictive than signals (52, p. 13; 53, pp. 322-323), I do not think that anyone would wish to recommend signals (with more stops, delay, queueing, and congestion) in order to achieve better operational quality and greater driver satisfaction.

For the design engineer, the difference in philosophy is perhaps whether to build for speed or to build for capacity. A philosophy developed for the construction of high-speed roads in the days when money was plentiful is not necessarily the most suitable for treating bottlenecks in times of severe inflation. But this paper does not deal with philosophy. It confines itself to describing the potential of modern rotaries, and the reader can decide according to his or her own philosophy what to do with the information. Nevertheless, when a highway department proposes the widening of a road, the elimination of a street jog, or the construction of an interchange, it would be expected to submit other feasible, prudent, and less harmful alternatives, together with its own recommendations and reservations. The fact that past and present design standards do not deal adequately with rotaries should not deprive the public of the benefits of a highly cost-effective TSM alternative.

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Publication of this paper sponsored by Committee on Operational Effects of Geometrics.

NOTICE

This paper was previously published in the ITE Journal (July 1979), without the three discussions and author's closure that accompany this version of the paper.

Highway Guide Signs: A Framework for Design and Evaluation

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Inadequate guide-sign design and location practices are responsible for a great number of instances of inefficient and potentially hazardous traffic operations within the highway system. Many of these deficiencies are rooted in inadequate highway system planning. The great majority of these locations, however, have operational problems that are directly related to the failure to coordinate guide-sign design and functional design as part of the highway development process. A framework for the coordination of guide-sign design with functional design is proposed and illustrated; emphasis is on the guide-sign development, design, and evaluation tasks. A computer program to plot perspectives was modified to provide the means of accurately depicting proposed guide signs within the perspective of a highway facility from the position of the driver's eye. The view presented by the perspective provides the designer with the third dimension—the view of the sign from the road. Shifts in vertical, lateral, and longitudinal sign position can be studied accurately by using the perspective as a tool. Examples were taken from two existing highway locations and provide the means for evaluating the suggested guide-sign design procedure for both existing and proposed guide-sign installations. Recommendations for further research and development are aimed at the reduction of the manual aspects of the procedure, thereby providing the designer with maximum incentive for investigation of alternatives, graphic details, and variations thereof.

Highway design philosophy, procedures, tools, and techniques have undergone rapid change in response to a recognized need for safe, efficient, environmentally acceptable, and economic highway facilities (1-5). The major objective of these studies, taken together, is directed toward the provision of a highway facility on paper that clearly satisfies recognized needs before construction and before the facility is put into operation.

Until recently, the driver and the driving task have been largely neglected by highway engineers; the driver has been obscured by gross statistical descriptions contained in design manuals, handbooks, and policies under the label of "driver and traffic characteristics." Since current research in human factors engineering, as applied to the driver and the driving task, are gaining more acceptance among highway engineers, attitudes are changing in the designers' approach to planning and design of new facilities and in refurbishment of obsolete highways. This attitude can be described as an awareness and concern for the driver and for facility operation; it incorporates a design philosophy that attempts to include the driver.

The need for recognition of new tools and techniques for design by the designer is absolutely necessary in order for him or her to deal effectively with obvious past deficiencies (obvious after the facility is put into operation). Why should accident experience or inefficient traffic operations be the prime motive for change and evolution of design procedures?

An important component of the design process is the design of the formal communications system for a highway facility. Guide signs constitute the most expensive part of the formal communication system, and they are the most permanent feature, other than the right-of-way and roadway surface.

Present costs (in 1977 dollars) of reflectorized, illuminated overhead and shoulder-mounted guide signs are on the order of \$300-\$400/m^2 (\$30-\$40/ft^2). This cost includes engineering, fabrication, delivery to the site, erection, and structures to carry the sign-panel display, along with illumination requirements. A typical kilometer of suburban freeway that contains one interchange may require an expenditure of more than \$50 000-\$100 000 for guide-sign needs. A careful, soundly based engineering approach is obviously required.

More important, however, is the highway engineer's awareness of the interaction of the guide sign and its message with the driver and the roadway. Guide signs are used by the driver primarily in the driving subtask of navigation. Failure of the formal information system (and, hence, of the highway facility) may, at worst, produce erratic driver response leading to accidents, injuries, and fatalities; at best, failure of the formal communication system may increase trip time and driver frustration and produce lack of confidence by the driver in what he or she perceives. Because the driver builds on past experience in the driving task, his or her skill is directly related to the ability to process information (6). Guide signs therefore play an important role in the successful operation of a highway facility.

It is a fact of driving experience that guide-sign legends and directional information are inadequate at numerous locations within our highway systems. There are many reasons for these apparent inadequacies, but one major cause is lack of communication within highway agencies—among those personnel responsible for system planning, functional planning and design, and design of guide signs. Many agencies separate the planning and design function from traffic engineering tasks, which normally include responsibility for design of guide signs. Usually, those whose responsibility includes guide signs are the last to become involved in the design and construction process.

Even sophisticated and time-consuming design review procedures have not satisfied or completely eliminated the resulting lack of coordination between the highway design and driver information needs. When so much effort has been expended in reaching the design review stage, the resistance to change or modification is naturally much greater. What is needed, therefore, is the direct involvement of sign designers in the functional planning and design stage; after all, if the facility cannot be signed, it should be modified. The functional design stage is where modifications should occur.

The balance of this paper deals with a description or proposal for linking guide-sign planning, design, and evaluation to the functional planning and design stage of the highway development process. In addition, a tool for evaluating a proposed sign or series of signs is described—a perspective-plotting technique wherein scaled sign-panel mock-ups are positioned within perspective plots. The results of a limited application of the perspective technique to actual locations are illustrated and described. Suggestions for further research and development outlined are subject to practical acceptance and testing of the technique illustrated.

COORDINATION OF GEOMETRIC DESIGN AND SIGNING

Highway System Planning Prerequisites

Before discussing the link between geometric design and signing, it is important to recognize that the guide-sign legend begins to take shape in the first stage of highway system planning where broad aspects are dealt with—route numbering system and other coding aspects, cardinal direction assignment, route classification, corridor studies, interfacing existing and proposed routes, etc. Results of these studies (which may be national, provincial or state, regional, or municipal) are used for progressively more detailed development of highway system components, such as freeway or arterial highway segments and interchanges, until the facility is finally designed, constructed, and put into operation. The importance of highway system planning in guide-sign legend development cannot be understated, because many of the inadequacies in guide-sign legends are seated in deficient system planning procedures. For example, inconsistent classification leads to difficulties in determining interchange form and route continuity; the choice of destination names or control city may not satisfy the through driver; incompatible cardinal route direction and actual direction may cause driver confusion; a change in route number along a rural facility that penetrates an urban area is confusing.

Rational aspects of highway system planning that are consciously or unconsciously appreciated by the driver include a network of routes that has cardinal direction association; a hierarchy of numbered route systems that reflect national, regional, and local routes; and a hierarchy of control destination names that reflects national, regional, and municipal destinations and is used in conjunction with numbered routes. Official highway maps reflect the above and form the basis of pretrip and enroute planning by a large number of drivers who have a reasonable level of driving experience. For example, the existing system in the United States is readily perceived by successive study of a map of the Interstate highway system, an official highway map of a state, and (finally) a street map of an urban area within the state.

This overview is necessary for the highway engineer. It provides an appreciation of the broad picture and enables him or her to view progressively smaller components of the system with an understanding of how everything fits together, and it is a necessary prerequisite for the succeeding steps in the design process. This overview is comparable to the use of high-level aerial photos first and then progressively lower-level photos in a route location and design assignment.

The second major category of guide-sign legend and location deficiencies can be associated with a lack of coordination between the guide sign and the roadway.

Function Planning and Design: The Logical Place for Guide-Sign Development

Lack of coordination of guide signs with the roadway result from a number of interrelated design deficiencies, such as lack of horizontal and vertical alignment coordination (sight losses and kinks), lane balance, route continuity, provision of basic number of lanes, lack of uniformity in successive interchange ramp configurations, and use of obsolete ramp geometrics and interchange types (5, 6). Other perceptual problems are more subtle and involve driver expectancies at all levels of the driving task: tangential exit ramps, dominant vertical elements adjacent to the roadside that create a wrong expectancy with respect to direction of major route (such as utility pole lines), large openings in the landscape at the end of long tangents, and railway-highway grade-separation structures parallel to the roadside (7).

Figures 1 and 2 illustrate several problems not anticipated even with careful design. These examples are drawn from an urban freeway project with which I was

Figure 1. Example of guide-sign panel design and location that need improvement: site 1.

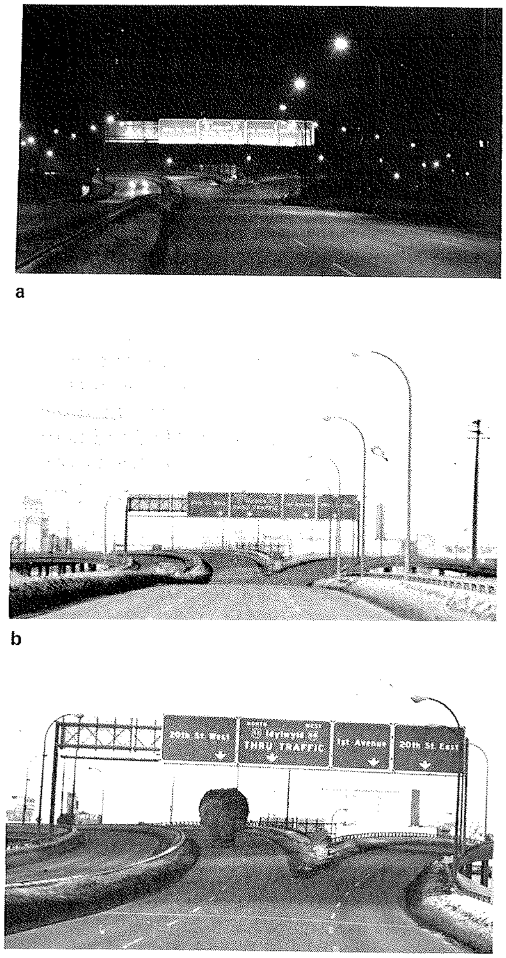

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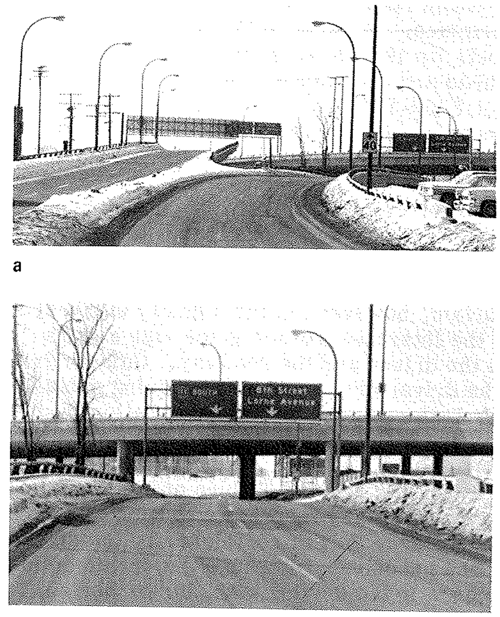
Figure 2. Example of guide-sign panel design and location that need improvement: site 2.



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associated. In Figure 1a, the view at night, note the obstruction of the panel at far right by the light standards and the problems caused by the position of the lighting. Figure 1b, the view in daylight, raises questions of whether relocation upstream or a diagrammatic alternative would improve effectiveness and whether the arrows on the two right-hand panels are ineffective. The closer view in Figure 1c, from about 100 m (330 ft), indicates that there are problems with the design of the route shields and that the THRU TRAFFIC sign is not meaningful. Figure 2a shows how signs for one roadway, across the parapet, may be read from another roadway and that down arrows may be meaningless around a curve. In Figure 2b, the down arrow on the left panel does not relate to the view of the roadway, the route shield is too small, and the display might better have been placed on the overpass structure in the background.

Many of these problems can be detected in the functional planning and design stage; this stage is therefore the most effective time to develop the guide signs for a segment of a highway facility. Figure 3 is a simplified flow diagram illustrating the relationship of functional planning and design to highway system planning and detailed design. Guide sign planning, design, and evaluation are depicted as a loop that uses the results of functional planning studies. Figure 4 is an expansion of the guide-sign task, commencing with preliminary guide-sign development and proceeding, step by step, to the preparation of contract documents.

Description of the Framework

The functional drawings, in plan and profile, provide reasonable base drawings for the superposition of proposed guide signs located by station in the plan and shown adjacent to the roadways in each direction of travel. Graphics of the sign panels should not be too detailed at this time, because the major question to be addressed is related to whether the proposed signing will work and whether the proposed geometrics can be signed by using recommended signing practices (8). Alternative signs for particular locations should be considered and displayed.

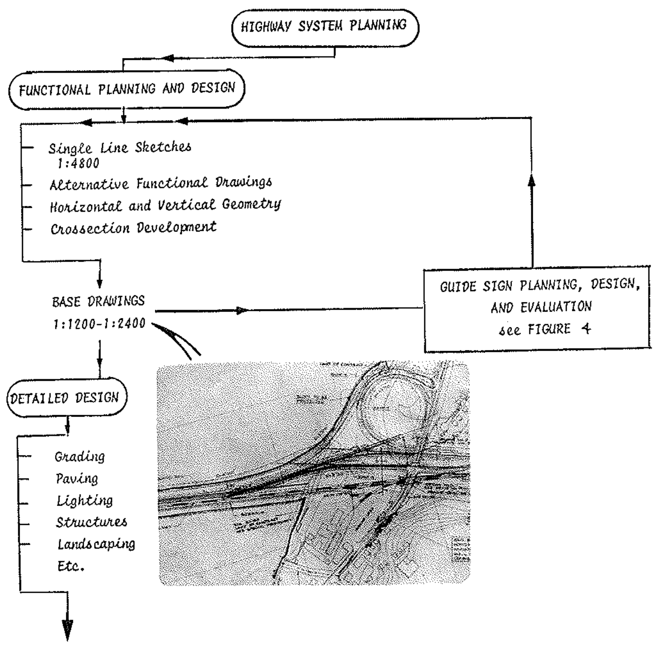
The designer then is in a position to acquire feedback by means of a design team review, in which other engineers and technicians involved in functional planning, system planning, and traffic engineering review separately, and as a group, the preliminary signing plan. Through the interaction of these individuals, revisions and adjustments can be readily made and a basic signing drawing agreed on, subject to detailed study of location, graphics, and coordination with other detail design tasks. The sign designer is then in a position to study in detail each sign panel and its alternatives by using a variety of signing principles and procedures recommended and described by King and Lunenfeld (9). Use of perspective plots in addition to these procedures provides the third dimension; the proposed guide sign is shown accurately within the perspective plot from the driver's eye. The designer is able to relate the proposed sign to the roadway much as the driver will in traveling along the proposed (or existing) highway facility.

USE OF PERSPECTIVE PLOTS

Perspectives of highway facilities, produced by means of a computer-driven plotter, have been used by designers to test for general visual quality of a proposed facility, detailed studies of horizontal and vertical alignment, aesthetics of bridges and overpasses, and safety-related improvements associated with fixed objects and modification to the roadside and median (4, 10, 11). Extension of this capability or tool for the study of guide signs was undertaken by using the perspective plotting program HWYPPLOT (11).

As Figure 4 showed, there are two main ingredients of a realistic perspective plot with proposed or existing guide signs superimposed: the first is an accurately scaled guide-sign mock-up; the second is knowledge of scale within the perspective at the location of the sign panel display.

Figure 3. Functional relationship of guide signs in the design process.



Scaled Guide-Sign Panel Mock-Up

Green card stock and pressure-sensitive white lettering are necessary to produce an accurate replica of a sign panel display. The dimensions of the Helvetica medium-letter alphabet and those of the series E alphabet used for guide sign legend are very close. Since there is an abundant selection of upper- and lower-case letters and numerals, a designer can use the normal range of letter and numeral heights found on guide-sign panels at a predetermined scale. Scales of 1:30 to 1:50 are common for detailed drawings of guide-sign panels, and experience has shown these scales to be suitable for the panel mock-ups. The legend of each panel is designed with proper letter spacing, interline spacing, and edge and border distances, and the white transfer lettering is overlaid on green card stock. Then, 35-mm slide or color film negatives of the mock-up form the basis for subsequent rear projection or direct mounting of prints of scaled guide-sign panel mock-ups on the perspective.

It should be noted that the scaled original mock-ups can be used for preparation of detailed drawings that form part of the contract documents for fabrication of sign panels (Figure 4).

Figure 4. A framework for guide-sign planning, design, and evaluation.

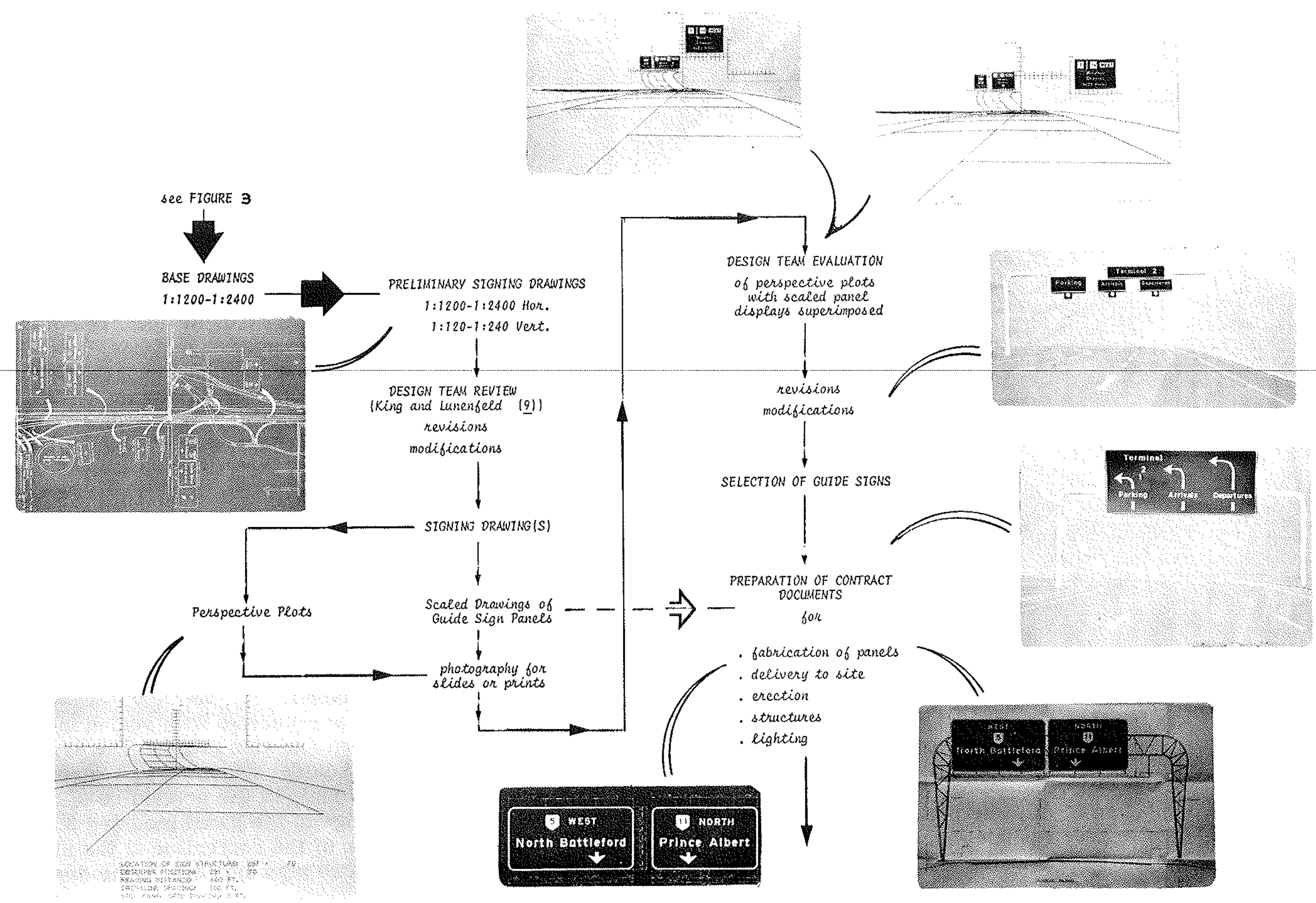


Figure 5. Typical perspective plot with shoulder-mounted and overhead guide-sign grids.

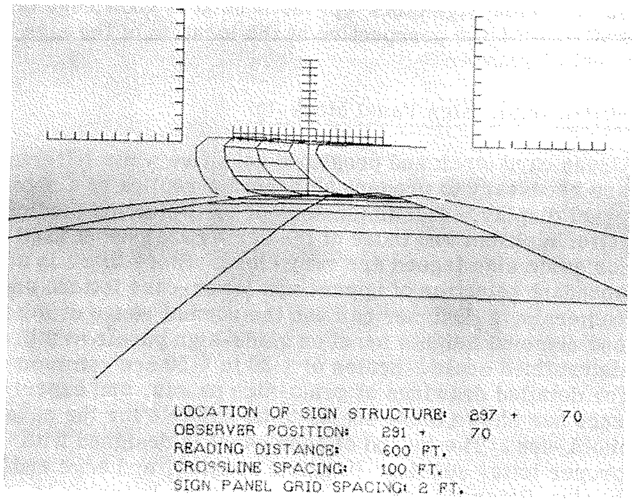


Figure 6. Perspective plot with exit-direction and gore signs mounted on sign grids.

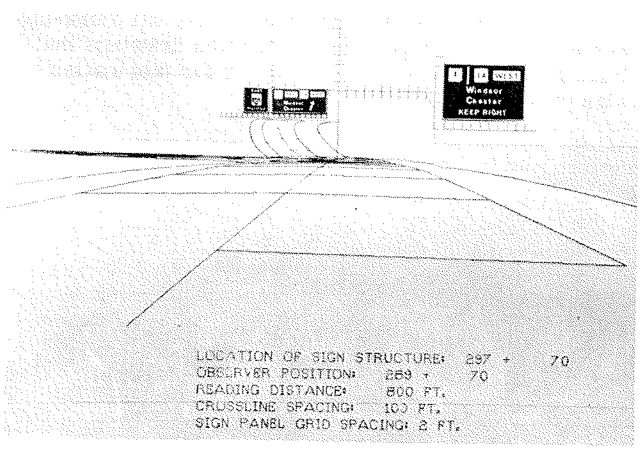
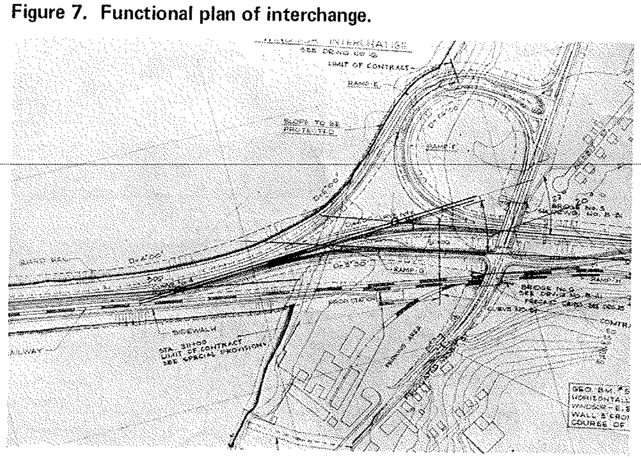


Figure 7. Functional plan of interchange.



The Perspective Plot

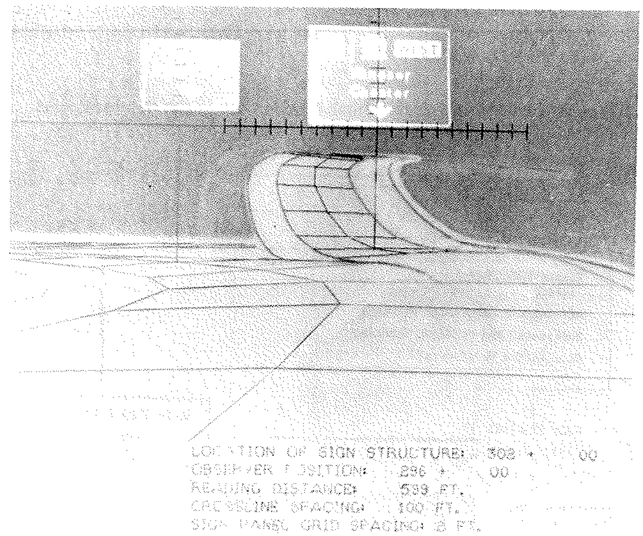
Accurate display of a guide-sign panel in a perspective of the highway facility requires knowledge of the horizontal and vertical scale at the location of the sign. A subroutine (12) was written for use with HWYPPLOT (11) to create, within the perspective, plotted grids that have a nominal size of approximately 0.67 m (exactly 2 ft).

Left and right shoulder-mounted sign grids, as well as overhead sign grids, can be specified separately or in combination for a single sign location or multiple sign locations that will appear from a particular driver-observer position. Figure 5 illustrates a perspective plot with sign grids.

The origin of the overhead grid is 5 m (16 ft) above the roadway centerline. Shoulder grids are located 2.5 m (8 ft) above the centerline and 6.7 m (22 ft) to the left or right. Selection of these origins leaves a portion of the grid visible after properly scaled guide-sign panel mock-ups are superimposed, because in practice a sign panel will normally be located away from the grid origin. Shifts in horizontal and vertical sign position can then be accurately studied.

Figure 6 illustrates a perspective with scaled mock-ups superimposed on the guide-sign grids. The arrangement of panels shows a shoulder-mounted exit-direction sign located 7.3 m (24 ft) right of the centerline of the roadway and the lower edge of the panel mounted 3 m (10 ft) above the elevation of the centerline at the sign position. An overhead gore sign appears in the distance

Figure 8. Existing gore sign installation and rear-projected guide-sign mock-ups.



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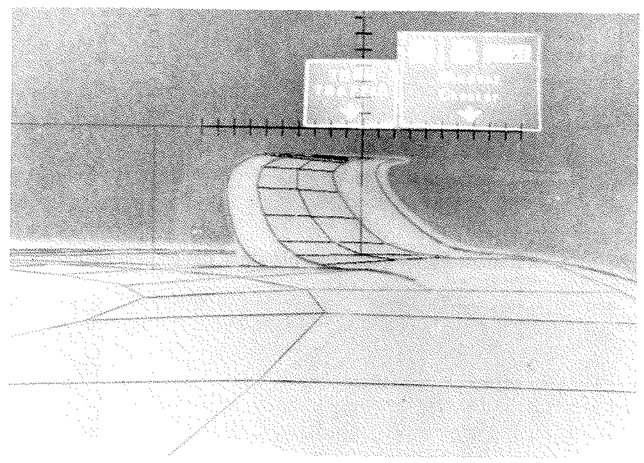

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and is mounted 5.5 m (18 ft) above the roadway centerline at the gore. A grid for an overhead exit-direction sign is also shown.

Use of the Perspective Plots to Evaluate Guide Signs

The following discussion is intended to expand on the use of the perspective plots within the framework of the process shown in Figure 4.

Knowledge of scale within the perspective allows the designer to mount properly scaled prints of panel mock-ups and, if 35-mm slides of the mock-ups are available, they may be rear-projected on the perspectives if the plot is made on a translucent paper.

By using these "complete" or composite perspectives as originals, the designer can rephotograph to produce a second set of slides or prints. These slides make it possible for a group or design team to review a proposed sequence of signs by projection on a screen. Panel shifts, sign location shifts, variation in panel legend graphics, and other problems can be studied with the assurance that the sign displays have been accurately depicted. Most important, however, is the added advantage of including the third dimension of the highway in the procedure where subtleties of geometry in three dimensions can be related to the proposed formal guide-sign information. Signs must relate to the view of the road beyond in order to confirm driver expectancy and provide positive guidance (13).

Up to this stage, the review of proposed signing is undertaken by highway engineers. Obviously, they are relatively biased evaluators and some degree of uncertainty remains, even though the resulting signs are based on sound design and operations principles.

A further test may remove some uncertainty and provide a more objective basis for acceptance or revision. A sample of drivers not involved with design of the facility would, most likely, be readily available to the design team from within the agency itself—clerks, stenographers, administrators, and technicians.

The perspective plots described above would form the basis for testing by the driver sample. While the design review team would not be bothered by the "raw" perspective plot, the test sample of drivers would probably find an embellished perspective more meaningful and realistic. Roadway color, texture, or joint lines, centerlines, edgelines, utility poles, and structures may be necessary to create a sense of realism for proper response evaluation. Tests could be designed to measure legibility, reaction time, and graphics.

ILLUSTRATIVE APPLICATIONS

An Awkward Curvilinear Exit Ramp

The first example concerns an exit ramp for an interchange of a two-lane, undivided highway that has grade-separated entrance and exit ramps. A portion of the functional plan is shown in Figure 7. Eastbound roadways are controlled by a causeway and gate structure. A rail line is located parallel to the highway. Restrictive geometry exists, largely because of the railway and causeway, in the form of 4° curves at each end of the causeway. Back-to-back 4° reverse curves exist in the interchange area.

At the advance reading position, the main line appears to have a slight kink to the left and then sweeps upward to the right. In reality, the main line curves left and the ramp continues on more or less the same tangent as the causeway approach roadway (see Figure 8). It is not until the driver is 100 m (300-350 ft) from the exit-direction sign that the main line and ramp begin to form in the driver's field of view. The main-line direction is not distinct because of its flat vertical alignment and the relatively sharp 4° curve.

The questions to be addressed here are (a) how realistic are the series of perspectives produced with mock-ups of the existing guide sign installation and (b) how might the existing guide signs be altered to improve the information presented to the driver? The reader will have to judge these questions in the light of the following illustrations and commentary.

Figure 8a projects the existing gore sign installation on the perspective plot at about 200 m (600 ft). Note the position of the left-hand panel. Since the main line is an undivided highway, the eastbound through-lane arrow appears to point downward to the westbound, or oncoming, traffic lane. Figure 8b illustrates the effect of moving the sign panels together and shifting them to the right by approximately 4.3 m (14 ft). The entire sign display now appears to lie directly above the approach roadway, and a better visual association of sign panel display with the highway results.

Figure 9 illustrates a more conventional (8) overhead gore sign installation in which the obsolete THRU TRAFFIC message is replaced by a distinctive through-traffic route shield and destination. Changes in lateral sign position are illustrated. In 9a the exit-direction arrow is closely associated with the ramp appearing below; 9b and c show the loss of association with a shift to the right. The sign positions shown in 9b and c seem to relate best to the approach roadway that appears below the sign display.

Figure 10 indicates a diagrammatic gore sign alternative. The importance of arrow geometry as it relates to the roadways below is evident. Figure 10a illustrates a first attempt; 10b and c show second and third trials for a diagrammatic arrow (shown in black) more closely related to the roadway below the sign panel. The sign appears to be located properly with respect to the approach roadway below the guide sign.

Airport Access Roadway

This example is concerned with a major airport's access roadway, the guide signs of which were the subject of a reaction-time and glance-legibility study by Dewar, Ells, and Cooper (14). The location of, and format for, advance guide signs for approach roadways to one terminal are illustrated here. There is a three-lane approach that splits into eight lanes immediately beyond a 90° turn. This creates an extremely short reaction time for drivers who find themselves in the wrong lane, not to mention the awkward visual appearance and relationship of this sign to the roadway below at a normal reading distance.

Properly scaled prints of the guide-sign mock-ups were positioned on the perspective sign grids. The alternatives in Figures 11b and c seem to be more effective in transmitting the message than the one proposed by the agency, 11a. Note the apparent increase in effect of the down arrows in 11b and c. Obviously the alternatives shown would be more costly but, on the other hand, they are probably more effective. (By comparing the unembellished perspectives shown in the first example, one can appreciate that the addition of pavement texture and pavement markings greatly improves the realism of the perspective.)

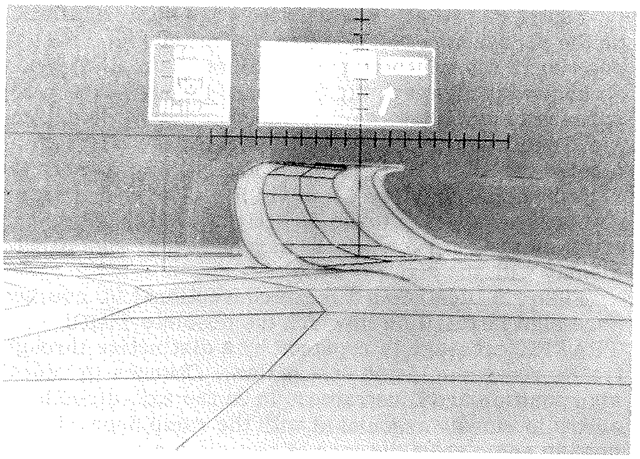
Other variations of alternative guide signs are illustrated in Figure 12, as well as variations in the driver's lane position. The diagrammatic alternative illustrated in 12c appears to relate better to the roadway and to be easier to read than the more conventional alternatives.

CONCLUSION

The usefulness of the perspective techniques for the evaluation of proposed guide signs and their position, legend, and graphics appears to hold promise and should be considered for use by highway agencies in new and reconstruction projects, particularly in locations that have extreme geometrics and in known problem spots. One positive feature of the use of the perspective plot is that it is an accurate and therefore objective portrayal of the roadway and sign, not an artist's perspective that is subject to individual artistic interpretation.

The illustrations show the connection between functional design and guide-sign position and, therefore, provide a strong argument for linking the functional design and guide-sign design processes. In the case of the tangential exit ramp, minor modification of horizontal and vertical alignment would have served to create a more positive guidance situation for the eastbound

Figure 9. Alternative rear-projected gore sign panels and mock-ups.



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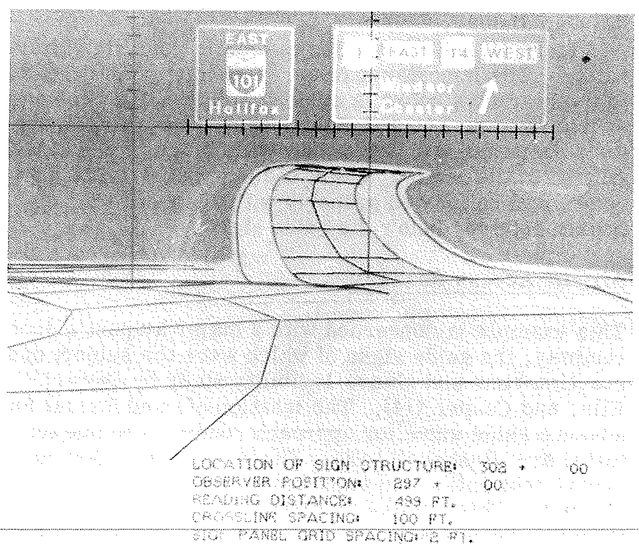

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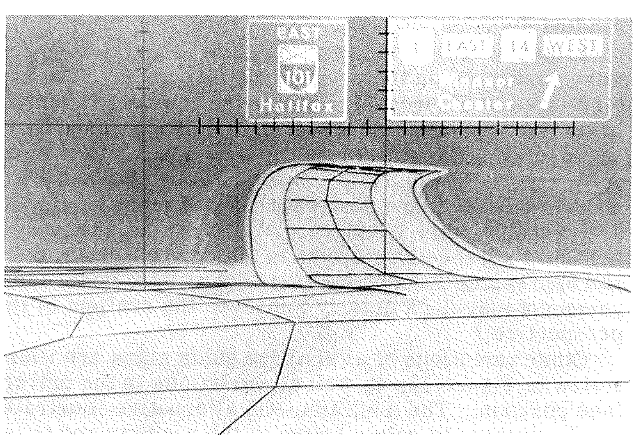

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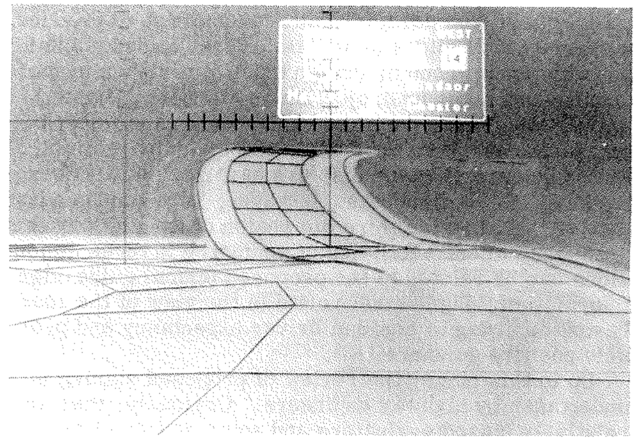
Figure 10. Diagrammatic gore sign alternatives.



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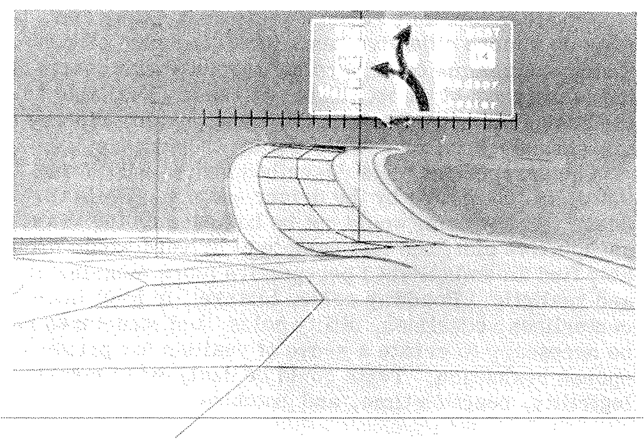

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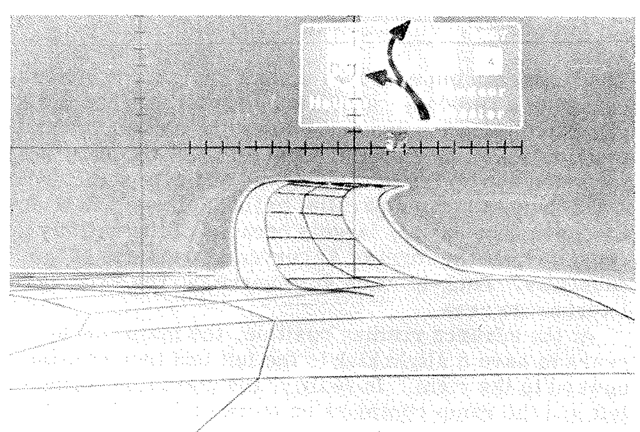

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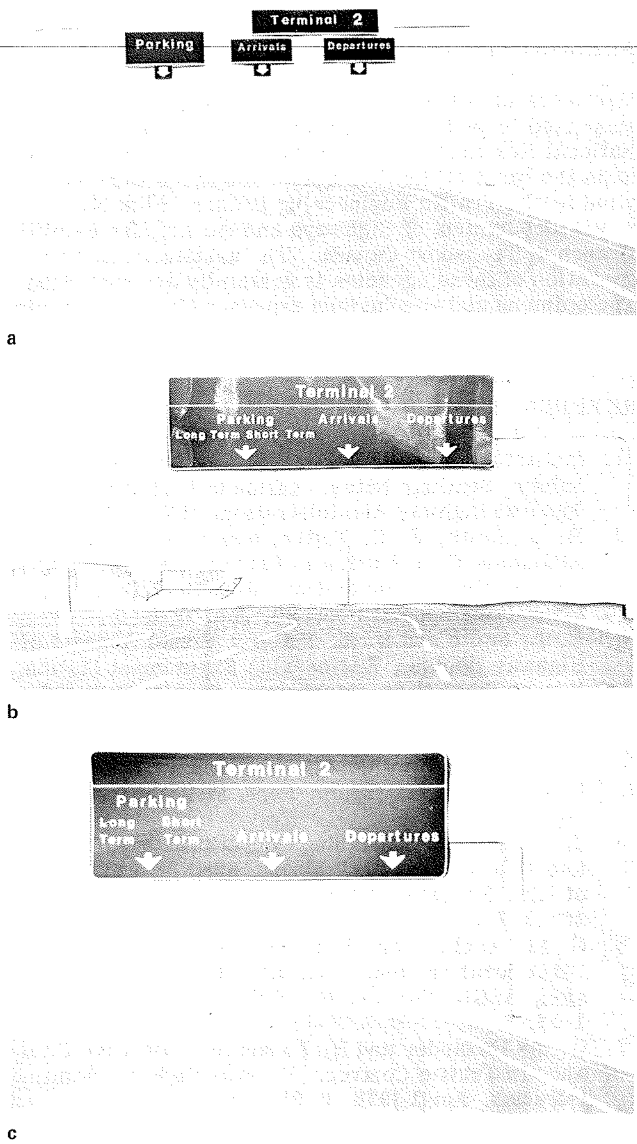

Figure 11. Existing and alternative advance signs.

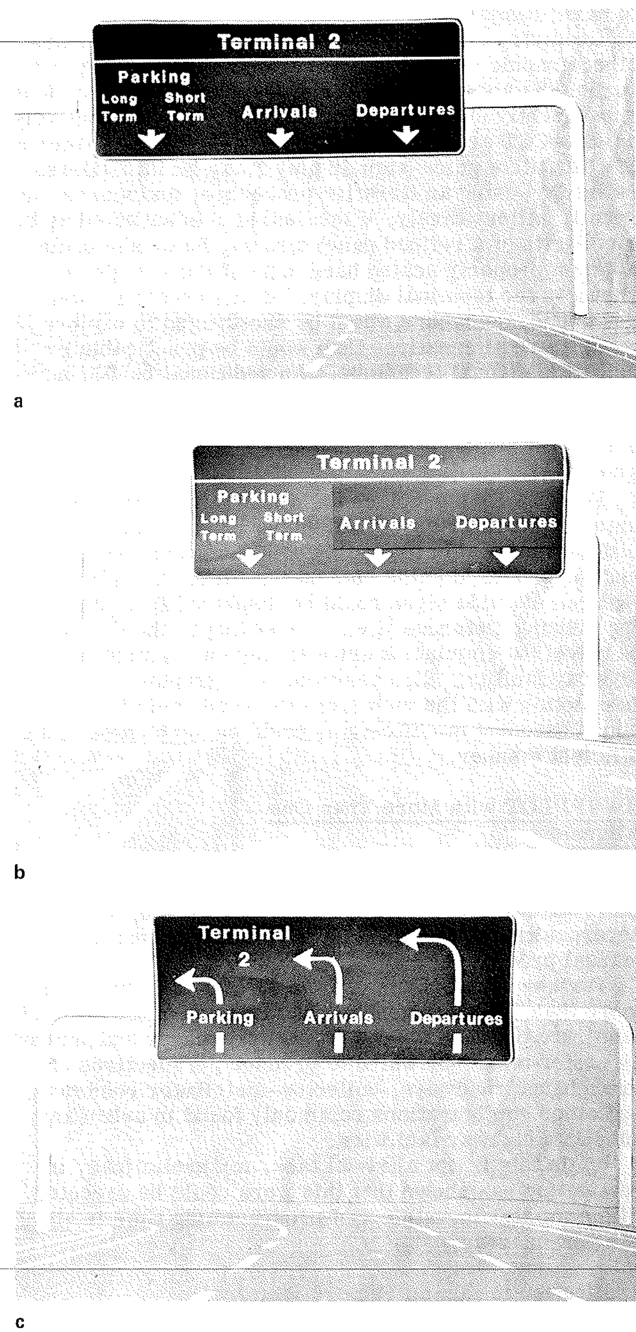

Figure 12. Alternative advance signs displayed from three driver positions.

driver; an overhead exit direction sign is better than the shoulder-mounted sign, and a diagrammatic gore sign might have merit.

The example of the airport access roadway provides definite evidence of a needed sign position shift, as well as a realistic view of a proposed sign and more visually pleasing alternatives thereto. The effect of embellishing perspectives with the addition of pavement markings and pavement texture is apparent.

Finally, the perspective view provides the designer with what Forbes (15) has referred to as "an intangible communication from the roadway and the general aspect it presents the motorist ... the complex interaction that may subtly, yet profoundly, influence motorists as they move along any given section of roadway." Further experiment and research, combined with practical use of the technique by highway agencies, is warranted and practically feasible.

SUGGESTIONS FOR FURTHER RESEARCH AND DEVELOPMENT

Should the procedures, techniques, and output described and illustrated here prove to be useful, the following suggestions should be explored with the objectives of minimizing manual aspects of the procedure and providing maximum incentive to the designer to explore a great number of sign display alternatives.

Toward an Automated, Scaled Guide-Sign Mock-Up

The most expensive aspect of the technique described is that associated with preparation of scaled guide-sign mock-ups. Even with substantial expenditure of time in the preliminary planning stage (see Figure 4), not many alternative sign legend and graphic possibilities can be practically studied; this is particularly evident in the graphics associated with diagrammatic signing. Recent developments in low-cost, interactive, computer-driven cathode-ray-tube (CRT) graphics terminals (16) appear to hold promise.

Geometry of alphabets, route shields, arrows, and other graphic variables (such as interline spacing, border distances, and letter spacing) can be stored and subsequently manipulated by the designer, interactively using a CRT graphics terminal. Thus, a large number of alternative guide-sign displays may be investigated, refined by using an iterative procedure, and stored for recall. Alternatively, if the designer is satisfied as to the merits of a refined panel display, he or she could obtain a properly scaled hard copy of the sign panel shown in the terminal display. If this capability were developed, designers would be encouraged to explore many more alternatives than would be practicable by using the manual technique. An additional benefit may lie in further research and investigation of the details of sign design: "optimum arrangement of message; advantage of symbolic or schematic signing; ... letter design details" (9).

Use of a CRT graphics terminal to interactively design and store guide-sign displays leads to the possibility of being able to display both the perspective plot and the proposed guide sign on the CRT. Complete sequences of guide signs could be displayed from decreasing viewing distances (i.e., proceeding in the direction of travel) to simulate a drive through a segment of a highway facility. Sign position, sign graphics, and their interaction with the view from the road could be studied, and subsequent modifications could be performed in an efficient manner.

HWYPPLOT with More Than One Alignment

The examples have described how both ramp and mainline roadway perspective plots are created by using a superposition of separate plots—a time-consuming, manual procedure.

Further development of HWYPPLOT to provide for more than one alignment in one direction of travel would eliminate the need for the manual procedure and provide an easier means by which to produce perspectives of interchange roadways, collector-distributor roadways, and other configurations commonly found in urban and suburban highway facilities.

While this is not a trivial task, my preliminary investigation has shown that this work could be executed with a modest investment of programming time in about one person-year.

Application in Human Factors Research

The preceding suggestions are essentially from the viewpoint of a highway engineer involved in planning, design, construction, and traffic operations.

A potential application of the techniques described is in the area of human factors research. In particular, would study of driver expectancy at the guidance and navigation level be enhanced by using perspectives with both formal information and highway geometry displayed? Would animation, using successive perspective plots, be useful? Would perspectives, as described herein, be a superior tool in glance-legibility and reaction-time studies (14)? Finally, would the techniques and products suggested be suited to study of the psychophysiological elements of visual syntax in a dynamic driver-oriented context? See, for example, a discussion of sign composition by Donis (17), which bears directly on the graphic consequences of message units and their position within a composition (or sign).

I hope that our colleagues in human factors engineering research will address themselves to these questions.

ACKNOWLEDGMENT

Development of the modified HWYPPLOT program was supported in part by my operating grant from the National Research Council of Canada. Design data that form the basis of the illustrative examples were supplied by the Traffic Engineering Branch of the Nova Scotia Department of Highways and the Airport Facilities Branch of Transport Canada. The assistance and cooperation of these agencies is gratefully acknowledged. The opinions and conclusions expressed herein are mine and do not necessarily reflect the views or policies of the cooperating agencies.

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Publication of this paper sponsored by Committee on User Information Systems.

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Abridgment

Formation and Dissipation of Traffic Queues: Some Macroscopic Considerations

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Queue lengths at signalized intersections are state variables that are frequently used for optimal control of traffic signals particularly at high-volume intersections. In the absence of a reliable macroscopic model that describes queue lengths as a function of the demands, intersection capacity, and the control decisions, existing control schemes are using effective queue size rather than queue length for optimal control. Effective queue size is defined as the actual number of automobiles waiting for service on a particular approach to the intersection at an instant. Queue length, on the other hand, is the distance immediately behind the stopline within which traffic conditions are on the right side of the flow-versus-concentration curve (i.e., they range from congested to capacity).

Anyone familiar with traffic signal control problems will recognize that queue length rather than effective queue size is the parameter that should be used to describe the state of the intersection. This is because an efficient signal control policy should prevent upstream intersection blockage; it should effectively control queue lengths rather than queue sizes. This criterion for optimal operations is somewhat relaxed when traffic demands are relatively low and queue lengths do not pose any immediate threat to adjacent intersections.

In this paper, a rigorous mathematical model shows the evolution of queue length in time at any approach to the intersection as a function of the demands, the intersection capacity, and the signal control policy. Due to space limitations, the results of the simplest possible model are given here. More detailed (therefore, more realistic) models, along with stability analysis and numerical examples, can be found in Michalopoulous and Stephanopoulos (1). The mathematics of queue dynamics discussed here can be used for optimal control of traffic signals. It is believed that, in light of these results, the traffic signal control problem can be placed on a new, more realistic, and rigorous framework of analysis.

BACKGROUND

Consider distance L behind the stopline of a particular approach to the intersection without entrances or exits. Further, assume that L is long enough so that queues never extend beyond this section. Within L, the following equation of continuity applies (2):

$$(\partial K/\partial t) + (\partial q/\partial x) = 0 \tag{1}$$

where

K = density,
q = flow,
x = space, and
t = time.

Assuming that flow is a function of density, that is, $q = f(K)$, it can be seen that Equation 1 is a first-order partial differential equation in which K is the dependent variable and x and t are independent variables. Solution of this equation allows the estimation of density at any point in the time-space domain. Although space limitations preclude a detailed presentation here, the solution of Equation 1 (also known as the continuity equation) leads to these conclusions.

1. Density K is constant along a family of curves called characteristic lines or characteristics.
2. The characteristics are straight lines emanating from the boundaries—x = L (stopline), x = 0 (end of the section), and t = 0—that have a slope tangent to the flow-concentration curve:

$$(dx/dt) \equiv h(k) = (dq/dK) \tag{2}$$

3. The characteristics carry the value of density at the point from which they emanate.

These findings suggest that density at any point that has the coordinates x and t is found by drawing the appropriate characteristic line emanating from one of the boundaries and passing through the point. The value of density at the boundary is carried through the characteristic line (i.e., it is maintained constant), and it corresponds to the density of the point of interest. If k_1 is