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Beyond The Green Book

Proceedings of the National Conference on Future Improvements to and Supplemental Guidance for AASHTO Policy on Geometric Design of Highways and Streets

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PART 1: CONFERENCE OVERVIEW

Beyond the Green Book--Future Improvements and Supplemental Guidance
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Introduction

The publication by the American Association of State Highway and Transportation Officials (AASHTO) of *A Policy on Geometric Design of Highways and Streets* in 1984 represented a major advancement in highway design. This document, commonly called the Green Book, replaced the 1965 AASHTO policy on rural highways and the 1973 AASHTO policy on urban highway and arterial streets. The document involved a major restructuring of the presentation of design criteria, guidelines, and standards. It reflects research and operational experience through 1983.

To avoid a long delay before the next update of the Green Book, AASHTO has initiated a program for managing the development of a revised Green Book manual. To provide input to this process, Transportation Research Board (TRB) Committees A3A08, Operational Effects of Geometrics, and A2A02, Geometric Design, conducted a conference on the subject November 9 and 10, 1987 in Austin, Texas. The conference was a combination of paper and workshop sessions to address the general need and means for achieving a systematic approach in the design process for reflecting the operational effects of geometric design. The Green Book was the major vehicle used to direct attention to this subject.

The conference was titled *Beyond the Green Book* to reflect two areas of focus that were desired. First, the participants were asked to assess the need for improvements in the Green Book for gaps in coverage, errors, and research not reflected in the policy. The participants were also asked to address the need for additional tools, techniques, and guidelines that could supplement the Green Book, and how the designer may employ them in assembling the design elements, established through the use of the Green Book, in such a way that a safe and efficient operation results. Conference products included both papers covering the subject and workshop recommendations for further improvement of the design process and the Green Book.

Background

A subcommittee was commissioned by TRB Committee A3A08 in January, 1984. It established a general goal to:

· Encourage the development of an objective and systematic means for reflecting the operational effects of geometrics in the design development process. The related objectives were identified as:

1. Define the design process and identify points along it where the operational effects may be reflected in decision-making.
2. Document, for the profession, what is being done now to reflect operational effects in the design process and in design decisions.
3. Develop research statements toward the development of models, tools, and procedures to assist the engineer in the design process and in making design decisions which reflect operational effects of geometrics

It was decided that both a conference session at the annual TRB meeting, and a mid-year working conference, would be appropriate mechanisms for achieving these objectives.

A conference session entitled Beyond the Green Book was held at the January 1986 TRB meeting. The arrangements for this session were made with or by TRB committees A2A02 and A3B06. Seven presenters spoke on:

a. State experience regarding the design process and means for reflecting operational effects,
b. Human factors considerations,
c. Applications of driving simulators,
d. Use of computer based models, and
e. Observations on the new Green Book.

A brief discussion followed. The session was well received, but there was a general agreement that much more time was needed to address the issues that had been raised. As a result, the concept of a workshop style conference was pursued by the committee.

An initial contact was made with AASHTO through Francis Francois, Executive Director, who suggested working with Mr. Brooks Nichols (Arkansas) who was Chair of the Task Force on Geometric Design. Mr. Nichols supported the conference concept and established a liaison with the conference committee. Unfortunately Mr. Nichols had to resign from the chairmanship of the task force and was replaced by Mr. George Sisson (Iowa). Mr. Sisson carried on the liaison and arranged for representation of the task force at the conference.

Conference Objectives and Structure

The objectives for the conference were:

1.Identify areas needing further improvement in the Green Book:

- Internal inconsistencies, and errors,
- New guidelines, and
- Changes dictated by recent research.

2.Identify tools and techniques to supplement the Green book and help the designer better reflect operational effects.
3. Develop a framework for the design process and identify the points along it where operational effects may be reflected and how they may be reflected, such as what tools and techniques apply.
4. Develop a research framework for improved design through better reflection of operational effects.

The first two objectives were identified as primary for the conference. The others, while secondary, remain important for providing the framework and the final product objective for this effort.

The conference format utilized a combination of invited presentations and working sessions. The program appears as Appendix A. The presentations were selected to provide both a general background and material specifically applicable to particular workshops that had been planned. Those presentations for which papers were prepared and approved appear herein as Part 3. Four workshop areas were provided:

1. Tools and Techniques to Reflect Operational Effects in the Design Process,
2. Means for Incorporating Operational Effects,
3. Opportunities for Updating and Enhancing the Green Book, and
4. Geometric Design Research to Support Improvement of the Design process.

For each workshop, a set of materials was prepared to facilitate the discussion. Each workshop was chaired by an invited attendee, who was assisted by a designated recorder. Workshop reports were presented and documented, and each workshop member was asked to complete an evaluation form. The workshop resource materials, reports and summaries of the evaluation forms appears herein as Part 2.

Summary of Presentations and Findings From the Conference

Overview of the Green Book

Frank Holzmann, representing the AASHTO Task Force on Geometric Design, initiated the discussion by providing the conference with an overview of the results of the previous month's task force meeting. He provided a chapter-by-chapter listing of the elements being considered for revision (see paper in Part 3). The more general comments on areas for action included:

1. The need to coordinate and refer to related manuals and documents, such as the *TRB Special Report 209: Highway Capacity Manual*, 1985 (HCM), *TRB Special Report 214*: *Designing Safer Roads: Practices for Resurfacing Restoration and Rehabilitation*, 1987, and the new AASHTO *Barrier Design Guide* which was about to be published.
2. The need to use care with language that has meaning in a legal context, such as "shall" versus "should".
3. The need to reflect the research conducted since 1983.
4. A complete review of the passing and stopping sight distance concepts.
5. The reflection of the influence of large trucks wherever necessary.
6. The need to relate to design and posted speeds.
7. Improved criteria to reflect acceleration and deceleration characteristics of the current and anticipated vehicle fleet.
8. Plan for a loose leaf version which will facilitate updating of sections.

The task force is working toward a regular update cycle of two years of the policy.

Two presenters gave their overview of the need for revision of the Green Book - one from a consultant's perspective and the other from a researcher's perspective. Joel Leisch started by offering a framework for the design process from a consultant's perspective (see Part 3). He pointed out that the new policy was an improvement in two basic ways:

1. Presentation of criteria by functional classification and
2. Modification of criteria based upon operational experience and research.

Mr. Leisch then suggested the following areas for primary consideration in upgrading the Green Book:

1. Use of a less rigid phraseology related to criteria and standards;
2. More responsive to experiences in litigation;
3. More criteria for urban projects for all functional classifications;
4. Better guidelines on how to compromise when it is not possible to comply with criteria;
5. The need for a description of a systems engineering approach to geometric design to reflect capacity operations, environmental, and other requirements;
6. A description of procedures to accomplish a design-plan, profile, and cross section.
7. A closer marriage between operations and capacity, and geometric design;
8. Emphasis on design consistency as it relates to operations; and
9. More comprehensive references.

Leisch proceeded to provide examples of the type of enhancements desired. Two final recommendations for the review and revision process were:

1. AASHTO should conduct a survey of users of the Green Book, and
2. The inclusion of several other related professional organizations in formulating future revisions.

John Glennon provided a researcher's perspective and the difficulty of producing a document using a voluntary committee approach, and also emphasized the importance of the document's effect across the United States. He rated highly the comprehensiveness of the document, its tie to other standards, and its use of graphics. Areas he noted as needing significant improvement included:

1. Use of optimization techniques,
2. Consideration of trade-offs,
3. Integration with traffic control needs,
4. Recognition of the need for flexibility,
5. Treatment of design consistency, and
6. Usability.

Glennon provided comment on some specific elements of the document, emphasizing heavily work needed on the various types of sight distance.

The Design Process and Tools

Douglas Harwood provided a proposal for a framework of the design process (see Part 3). This starts with the statement of specific goals in the areas of safety, efficiency, economy, comfort, maintainability, and environmental quality. The second stage involves the definition of basic constraints and interactive relationships that control the design process, especially with regard to the driver's capabilities and limitations. The next stage of design involves relating the goals and constraints to the possible design elements so measures of effectiveness may be determined. This modeling of the system allows for the selection of the appropriately combined design elements.

Harwood pointed out the need to reflect this process at each stage of design development. He then went on to provide specific details on how operational effects may be reflected through selection of functional classification, design speed, and design vehicles, as well as in the conduct of highway capacity analyses.

Richard Michaels provided an overview of a human factors approach to understanding the relationship between geometric design and observed traffic behavior (see Part 3). A basic model is proposed which focuses on the sources of information inherent in the geometry of the roadway, that allows the drivers to locate themselves in time and space. The model uses motion in the visual field as the basis for analyzing driver behavior. This kind of model permits a direct analysis of the geometric characteristics of the highway for driver response and hence, traffic behavior. He demonstrates the use of the model by applying it to specific geometric elements, and points out that it will lead to some different results from those which appear in the Green Book.

William Wiedelman presented concepts for applying Computer Aided Design and Drafting (CADD) systems to evaluate highway design elements (see Part 3). The use of the graphical representation of a design and its ready manipulation in a CADD environment facilitates the analysis of aspects such as, sight distance. In addition, the CADD file may be used as a database for entering geometric features into supplementary analyses such as those used in the HCM.

Brian McHenry demonstrated the use of the Highway Vehicle Object Simulation Model (HVOSM) for the purpose of evaluating geometric design elements (see Part 3). This computer simulation model has been in development and refinement since the mid 1960's. It has been applied on several Federal Highway Administration (FHWA) research projects dealing with the determination of design guidelines. McHenry discussed a few of these, including the comparison of vehicle paths on various horizontal curve designs. The human factors elements of the model were noted as needing improvement for such applications, but the model has been useful in providing insights not otherwise attainable. Furthermore, it has been used on specific projects in addition to general research.

Geoffrey Gosling provided the conference with an introduction to expert systems. He outlined the techniques used for knowledge representation and control of the inference process, as well as the sequence of steps involved in the development of an operational expert system. This field is in its infancy, but is attracting a lot of interest in the military and other professions. Gosling described two experimental systems in highway design. The first provides advice on approach lane configurations of a signalized intersection, while the second uses design standards and sight constraints to recommend horizontal and vertical alignment. He completed his presentation by pointing to future applications involving route selection, interchange design, and reconstruction planning

Mark Wolfgram brought the conference back to earth with some very practical examples of economic evaluation tools which have been developed for use in decision making involving alternative highway designs.

Three examples were presented:

1. Life cycle cost analysis for pavements,
2. Accident evaluation, and
3. Speed and operating cost estimation.

The examples demonstrated how commercially popular spreadsheet programs for microcomputers and specialized software developed for these purposes can be used.

Overview of Recent Research

George Pilkington provided the conference with an overview of recent research that applies to the update of the Green Book. He pointed out that there are several reasons that research is not used, especially in the near term after completion of the project. These include a natural resistance to change and a fear of litigation. Also discussed was the limited publication and dissemination of reports from the FHWA, due to budget reductions. He presented the results of a tabulation of recent research versus the problem areas cited in a survey of AASHTO agencies. The listing (see Appendix C) demonstrates the number of studies which are available to the task force. Two areas noted as needing additional research were:

1. Ramp spacing guidelines, and
2. Conflict between the Green Book and the Manual on Uniform Traffic Control Devices (primarily in definitions).

As an example of current research, and a further indication of how the human factors approach may be applied to design, William Reilly reported on the progress of a current National Cooperative Highway Research Program (NCHRP) project which has the objective of arriving at new design guides for speed change lanes using a human factors approach. A model has been developed for testing which utilizes angular velocity threshold as the objective criteria for gap acceptance. This was being applied to relative speed and volumes on the ramp and mainline. A framework for application of the concepts was also presented. The resulting product will be a proposed section for the revised Green Book.

Workshops

John Mason provided a summary of the issues to be addressed in the workshops, based upon the presentations and his own perspective. In addition to adding material on the design process, he emphasized the need to define the highway's functions in the Green Book. This would include incorporation of access control strategies, provision of an overview of planning models and techniques, and an expansion of functional classification as a design type.

Mason also emphasized the need to address the driver more comprehensively, including such aspects as perception reaction time limitations of the human controller, the design driver concept, consideration of the difference between the commuter and recreational driver, and some philosophy regarding design responsibility to account for driver errors. And finally, he encouraged discussion on:

1. How the document could be made conducive to updating;
2. The use of example design problems, as in the HCM, with emphasis on rehabilitation work;
3. Expanded references;
4. References to applicable computer programs;
5. Use of expert system approaches; and
6. Integration of CADD as a design tool.

The recommendations and further details on the results of the workshop discussions are provided in the following section.

PART 2A: WORKSHOP SUMMARIES AND RECOMMENDATIONS

By: R. Kenneth Shearin, Roy Jorgensen Associates, Inc.

Background

The second day of the conference was primarily devoted to workshop sessions on several issues related to geometric design. This included a discussion of four topics:

1. Workshop Session 1: Tools and Techniques to Reflect Operational Effects in the Design Process;
2. Workshop Session 2: Methods for Incorporating Operational Effects;
3. Workshop Session 3: Opportunities for Updating and Enhancing The Green Book; and
4. Workshop Session 4: Geometric Design Research.

The objective of the workshops was to provide an informal forum to discuss these issues. The participants discussed their experience in using the Green Book and presented ideas on how its utility to the highway design community might be improved. Each workshop group generated specific recommendations based on the discussion among its participants.

The workshop sessions resulted in very interesting and productive discussions. This can be attributed to the excellent performance of the workshop session leaders. As requested, each leader followed the basic structure of the prepared workshop materials, but also allowed the discussion to develop spontaneously as dictated by the interests of the participants. The afternoon presentations from each session leader clearly indicated the scope and depth of the workshop discussions.

Attendance

The attendance in the workshop sessions, and at the entire conference, provided a diversified background. This enabled the discussion to draw upon a variety of experiences and frames of reference. Table 1 summarizes the attendance composition for each workshop session.

Recommendations

The following discussion presents a summary of the more significant recommendations and observations which were generated by the workshop sessions. They are categorized according to the major topics which were addressed by the workshops.

The opinions on any particular issue varied widely. This would be expected from a sizeable group of professionals with diverse backgrounds and experience. The observations which follow reflect what appear to be consensus views. These are determined from the reports submitted by the session leaders and from the results of the evaluation forms submitted by the workshop participants. Each participant provided ratings of his or her views on the values of various aspects of geometric design, operational techniques and the Green Book.

TABLE 1 WORKSHOP ATTENDANCE

Organization	Workshop Session						
	1	2	3A	3B	4A	4B	Total
State Transportation/ Highway Agency	3	2	8	7	3	2	25
Design Consultant	5	2	1	1	2	-	11
Research Consultant	1	-	-	-	2	3	6
University/Academic	-	2	-	-	-	4	6
Municipal Agency	-	1	-	1	-	1	3
Federal Agency	-	-	-	1	1	1	3
Port/Turnpike Authority	1	-	-	1	-	-	2
Totals	10	7	9	11	8	11	55

Systematic Design Process

Workshop Sessions 1 and 2 addressed the feasibility of a systematic design process. The following summarizes the more significant conclusions which can be determined from the workshop products:

1. *Existing design process*. The overwhelming consensus view was that the existing design process performs adequately but needs improvement.
2. *Applicability of a systematic design process*. The two most frequently expressed opinions (17 responses total) were that a systematic design process:
   a. "Appears to be very promising and should be pursued vigorously" (7 responses), and
   b. "Appears to have some merit and may warrant further investigation" (5 responses).
3. *Research*. The overwhelming consensus view was that the highway community should embark on a major research effort to gather the necessary input data for a systematic design process.

4. *Probability of success*. The consensus view was that the implementation of a systematic design process has a medium probability of success.

5. *Applicability to Green Book*. Regarding the systematic design process, the workshop participants in session 2 were evenly split between recommending that:

a. A separate, stand-alone chapter be included in the Green Book and

b. A separate publication be prepared on a systematic design process.

Operational Tools and Techniques

Workshop Sessions 1 and 2 addressed several existing and needed tools and techniques which reflect the operational effects of geometric design. Much of the workshop discussion addressed specific operational techniques, for example, roadside and cost-effectiveness. The following summarizes the more significant overall conclusions which can be determined from the workshop products:

1. *Existing techniques*. Many techniques have been developed to evaluate the operational effects of a wide variety of geometric design elements. Some design agencies and consultants currently use some techniques on a routine basis. However, the level of familiarity with and extent of their usage is not especially high.

2. *Potential benefits*. There was a general consensus among the workshop participants that the widespread application of operational tools and techniques would result in significant benefits to highway design. Further, the expenditure of resources by the highway agency would probably be justified.

3. *Design process integration*. The workshop participants reached a general consensus that the operational techniques could be successfully integrated into either the existing design process or into a more systematic design process.

4. *Green Book integration*. The participants in one workshop presented a wide variety of views on the recommended revision of the Green Book to reflect operational techniques. Any observations must be tempered because only three techniques were evaluated. However, the following conclusion might be appropriate: Most operational techniques are of such a nature that a reference in the Green Book, perhaps with an overview discussion and or a separate publication, would be appropriate.

5. *New and improved techniques*. The participants in one workshop presented a recommended list of operational techniques that either should be developed or an improvement made to the existing models:

a. Cost effectiveness,

b. Stopping sight distance profiles for the combined effect of horizontal and vertical alignment,

c. Passing sight distance profiles, and

d. Speed profiles for passenger cars and trucks.

Enhancing the Green Book

Workshop session 3A and 3B discussed several opportunities for enhancing and updating the Green Book. These sessions evaluated specific topics which are addressed, in varying degrees, in the Green Book. Table 2 presents the rankings and aggregate ratings for the topics which were discussed. The summaries of the workshops in Part 2 provide more detailed information. The specific nature of the discussion for each topic is presented in the resource materials in Appendix G. There, the reader will find many detailed observations on the individual geometric design elements.

The reports of the session leaders noted several other observations which generated discussion among the workshop participants. Some of the more important are listed:

1. *Green Book revisions*. According to one group, most of the users of the Green Book are reasonably satisfied with its technical content. Any needed revisions are viewed as fine-tuning rather than a major overhaul. One workshop group recommended that the ongoing Green Book revision should continue as planned.

2. *New versus existing roads*. One workshop consistently recommended that the Green Book should make a distinction between new construction projects and projects on existing roads.

3. *Economic considerations*. One workshop recommended that many geometric design decisions should be made on the basis of economic trade-offs, perhaps by a formal cost-effectiveness analysis.

4. *Other topics*. Although not formally evaluated, one workshop suggested that the following items merit further consideration:

a. Benefits of spiral curves,

b. Compatibility between geometric design and traffic control devices,

c. Geometric design through construction zones,

d. Warrants for right-turn lanes, and

e. Superelevation on curves at the end of long downgrades.

TABLE 2 WORKSHOP SESSION #3 EVALUATION

OPPORTUNITIES FOR UPDATING AND ENHANCING THE GREEN BOOK

Rank	Title	3A Rating	3B Rating	Aggregate Rating
1	Application of Stopping Sight Distance	8.6	9.2	8.9
2	Intersection Sight Distance	8.1	8.3	8.2
3	Design Speed	7.6	7.4	7.5
4	Roadside Clear Zones	7.1	7.4	7.3
5	Cost Effectiveness*	-	6.6	6.6
6	Shoulder widths	6.7	6.4	6.5
7	Detour Design (Geometrics)*	-	4.3	4.3
8	Driveway Design	2.7	3.8	3.3

*Generated by Group 3B.

Geometric Design Research

Workshop session 4A and 4B addressed candidate topics for further research in geometric design. Table 3 presents the rankings and aggregate ratings for the topics which were discussed. As indicated, workshop session 4B discussed and evaluated six topics which were not included in the list of prepared topics.

The reports of the session leaders noted that several other items were discussed during the workshops. Some of the more important ones are listed:

1. *Implementation of research.* One workshop group identified a need to develop and routinely disseminate a synthesis of research to assist the highway design community in research availability. Specifically, the group discussed the unavailability of Federal Highway Administration (FHWA) R&D reports. The group suggested that, at a minimum, there should be a frequently updated mechanism through which interested users could determine which reports are available through the National Technical Information Service (NTIS).
2. *Green Book development.* One workshop group concluded that the development of the Green Book should be open to additional professional groups, especially those who are day-to-day users. In addition, there should be a dedicated staff and funding for revising the Green Book. The development of the Highway Capacity Manual, 1985 (HCM) was cited as an example which might be used in the Green Book development.
3. *Geometric design approach.* One workshop group noted that, for some geometric design elements, a worst-case scenario is assumed, but for others an average condition is assumed.

TABLE 3 WORKSHOP SESSION #4 EVALUATION

GEOMETRIC DESIGN RESEARCH

Rank	Title	4A Rating	4B Rating	Aggregate Rating
1	Integration of Research Results into AASHTO Geometric Policy*	-	8.1	8.1
2	Overview of Sight Distance Model*	-	7.9	7.9
3	Reduced Lane and Shoulder Widths on Urban Freeways	6.8	7.2	7.1
4	Left-Turn Lane Warrants*	-	7.0	7.0
5	Expert Systems to Relate Geometric & Traffic Control Devices*	-	6.9	6.9
6	Stopping Sight Distance	5.8	6.6	6.3
7	Roadside Design Elements*	-	6.3	6.3
8	Relationship Between Geometric Design Elements & Traffic Control Devices	5.8	6.4	6.2
9	Litigation Problems*	-	6.1	6.1
10	Intersection Sight Distance	5.2	6.1	5.8
11	Relationship Between Accidents & Geometric Design	3.8	6.1	5.3

* Generated by Group 4B

Workshop Summaries

The following discussion presents the summaries of findings from each workshop as provided by the workshop sessions leaders. Each workshop group was provided resource materials which were used to guide the discussions. These are presented in Appendix G. However, it should be noted that the discussions in several sessions and the resulting recommendations were broader in scope than the content of the resource materials.

Summary of Results

Workshop Session 1: Tools and Techniques to Reflect Operational Effects in the Design Process

Workshop 1 focused on tools and techniques for use in the design process that reflect key operational effects of design elements. Workshop participants discussed the following areas:

1. The identification of existing operational tools and techniques, and the extent of their current use within the design process;
2. The identification of desired or needed tools and techniques, not currently available, to assist designers; and

3. The design process, how it aids or hinders operational evaluation of designs, and how the identified tools and techniques could be applied to design.

Existing Operational Tools and Techniques

The workshop participants identified several operational tools and techniques, some of which are currently used by design agencies as they develop and refine plans. Table 4 summarizes these tools and techniques.

Participants generally agreed that all the techniques were useful in evaluating and refining design work. It was noted that some agencies and consultants currently apply these tools on certain types of projects. The following examples are notable:

1. The Wisconsin Department of Transportation is currently investigating the use of a computerized roadway inventory to identify inconsistent designs on two-lane rural highways. They are employing the Leisch speed profile method and also investigating accident rates at certain locations.
2. Consultants working for the States of Arizona and Iowa have employed speed profiles on two-lane highway and freeway projects to evaluate operational quality of alinement.
3. The Wisconsin Department of Transportation has refined and improved techniques for determining highway user costs for assisting in project programming and alternatives selection.

It was noted that many of the techniques, while known to the profession, were cumbersome in their current application formats. Development of computerized analysis techniques was recommended by the workshop for the following operational models:

1. Relationship between user costs and geometry shown in the 1977 AASHTO Manual on User Benefit Analysis for Highway and Bus Transit Improvements;
2. Roadside safety relationships and model features from NCHRP 148;
3. Stopping sight distance profiles for the combined effect of horizontal and vertical alinement of a highway. This was identified as a particularly important application of Computer Aided Design and Drafting (CADD) technology; and
4. Enhancement of traffic operational and safety analysis available in software provided with CADD systems including:

· Stopping sight distance profiles for the combined effect of horizontal and vertical alinement,
· Passing sight distance profiles and locations of passing and no-passing zones, and
· Speed profiles for passenger cars and trucks and identification of design inconsistencies.

TABLE 4 OPERATIONAL TOOLS AND TECHNIQUES

Operational Analysis Tool/Technique	Design Features Applied To	Reference
Speed profile	Horizontal and vertical alignment (consistency of design)	(1)
Speed profile (curvature change rate)	Horizontal alinement	(2)
Design consistency (driver work load)	Horizontal and vertical alinement, narrow bridges, intersections, etc.	(3)
Roadside accident model	Cross section, clear zone	(4)
Highway user operation costs	Horizontal and vertical alinement	(5)
Sight distance profiles	Stopping sight distance, horizontal and vertical alinement, intersection location and design	(6)
Highway capacity	Highway sizing, horizontal vertical alinement, intersection design	(7)
Alinement compatibility	Horizontal and vertical alinement	(8)
Safety relationships (two-lane rural)	Horizontal and vertical alinement, intersection design, bridge width, cross section	(9)

The workshop participants also noted the availability of existing computerized tools for evaluating operations of various highway types. Design agencies are encouraged to review and apply these tools in preliminary design. The computerized models identified by the participants are:

1. FREQ8PE: A macroscopic traffic flow model used to evaluate freeway design and operational strategies, including ramp configuration, ramp metering, and High Occupancy Vehicle (HOV) strategies.
2. TWOPAS: A microscopic traffic simulation model for two-lane highways, including the capability to simulate passing and climbing lanes.
3. ROADSIM: A microscopic traffic simulation model for two-lane highways.

Other Analysis Procedures

Representatives of State Departments of Transportation and consultants also noted the importance of design standards and criteria reviews as part of the 3R and 4R process. The States of Arizona and Florida routinely review the existing highway in comparison with the latest criteria and guidelines from the 1984 AASHTO Manual. One consultant has developed and refined a technique for depicting the quality of an existing freeway's design characteristics before investigation of reconstruction alternatives.

Cost Effectiveness

The workshop participants reached a strong consensus regarding the need for the profession to apply cost-effectiveness analysis in 3R and 4R problem solving. It was generally agreed that blanket application of AASHTO values from the 1984 Green Book will often not result in the most cost-effective design. Both operations and safety are key features in determining cost-effectiveness. The 1977 AASHTO User Benefit Analysis Manual was identified as a key publication, providing a cost-effectiveness methodology. The Transportation Research Board *Special Report 214: Designing Safer Roads*, was identified as a key publication for determining safety measures of effectiveness.

The Green Book should refer to the above documents, and should address the appropriate procedures and techniques for cost-effective design decision-making. In particular, it was the consensus of the workshop that policy should explicitly encourage the use of cost-effectiveness analysis in determining appropriate design for highway reconstruction and rehabilitation projects. Information on the safety and operational effect of various designs would be extremely useful in this process.

Design Process

Much discussion in the workshop centered around the design process and how it could be improved to assure operational efficiency and cost-effectiveness. Some problems were noted in the process as it typically is carried out.

1. *Segmentation of tasks*. Execution of final plan preparation typically is carried out by designers with little or no operations experience or knowledge. Operational consistency built into the plan during the planning and preliminary engineering phases may be sacrificed unknowingly by final design decisions.
2. *Lack of guidance in Green Book*. The design process is not explained in the Green Book. Previous editions included discussion and examples of how the operational needs of a highway were translated to the plan itself. Several workshop participants believed that a discussion, either in an appendix or separate chapter, would be a valuable addition to future editions of the Green Book.

Recommendations regarding the above two problems were made. It was the consensus of the workshop that:

1. The Green Book should include or provide detailed references to documents on operational and safety relationships.
2. The Green Book should explicitly cover the design process. Checklists of operational considerations and design activities would be useful to aid users.
3. A companion document or documents with the latest synthesized traffic operational and safety research should be developed and periodically updated to support design decision-making.
4. The agencies responsible for design should perform operational "checks" of final plans prior to construction, to assure that design compromises have not adversely affected the intended operational quality and design consistency.

Evaluation by Workshop Participants

The following discussion presents a summary of the evaluation performed by workshop participants on the potential for improving highway geometric designs through development of a more systematic design process along the lines suggested by Harwood and Glennon (10), and in the presentation at the conference on reflecting operational effects throughout the design process.

The following questions were asked of the workshop participants:

1. What type of agency do you represent?

State Transportation/Highway Agency	3
Design Consultant	5
Research Consultant	1
Other	1
	10

2. How would you evaluate the present design process in the United States?

	State Agency	Design Consultant	Research Consultant	Other	Total
Not seriously flawed; usually results in a highway design which is compatible with its operating environment.	0	0	0	1	1
Needs improvement, but performs adequately.	3	5	1	0	9
Is seriously flawed and needs a major overhaul.	0	0	0	0	0
	3	5	1	1	10

3. How would you evaluate the applicability of a systematic design process?

	State Agency	Design Consultant	Research Consultant	Other	Total
Appears to be very promising and should be pursued vigorously by the highway community.	2	3	0	0	5
Appears to have some merit and may warrant further investigation.	1	0	1	1	3
Some aspects appear promising and these should be incorporated in the existing highway design process.	0	2	0	0	2
Appears to be theoretically sound, but is unlikely to work in practice	0	0	0	0	0
Appears to have little or no practical value	0	0	0	0	0
	3	5	1	1	10

4. Should the highway community embark on a major research effort to gather the necessary input data for a systematic highway design process?

	State Agency	Design Consultant	Research Consultant	Other	Total
Yes	3	4	1	1	9
No	0	0	0	0	0
Not sure	0	1	0	0	1
	3	5	1	1	10

5. The highway design community could strongly pursue the implementation of a systematic approach to highway design. How would you characterize the probability of success?

	State Agency	Design Consultant	Research Consultant	Other	Total
High	1	1	0	0	2
Medium	2	2	1	1	6
Low	0	2	0	0	2
None	0	0	0	0	0
	3	5	1	1	10

Other Comments

1. The design process needs an overhaul to reflect cost-effectiveness considerations, especially for rehabilitation projects (research consultant).
2. The most important things to be done are documenting the operational effectiveness and implications of design values, transmitting that knowledge to designers, and reviewing final plans of projects to check that operational effectiveness has been retained (design consultant).
3. Process and policy have to be integrated to achieve desired design performance (design consultant).
4. It must be strongly emphasized that some group must take a leadership role if a systematic design process is going to be achieved. That group must also be adequately staffed and funded (state agency engineer).
5. The Green Book should be made more flexible, a guide, not a standard. The term "shall" should be changed to "should" (state agency engineer).
6. Good designers intuitively make sound engineering judgements which reflect the operational tools and techniques discussed in the workshop (design consultant).
7. The highway design community is low-tech and not subject to rapid change. There is too much conservativeness and inertia to move the profession. It will take a considerable amount of time to implement a systematic approach to design, which will lessen the chance of success (design consultant).

8. It is important for a design process description to provide guidance for the overall design process and not to become too specific about specific tools or mechanisms for accomplishing the design. The tools to implement the process can be made available to the designers to be used or not used at their discretion, as long as the process is adhered to (design consultant).
9. If the Green Book is really a policy on design, it should include a discussion, some guidelines, and checklists on the design process. One serious gap to be addressed is that between research efforts, reports, and the Green Book (state agency engineer).
10. CADD and microcomputer technology should make it easier to achieve design consistency. Standard software for evaluating factors could be used (other agency).

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Summary of Results

Workshop Session 2: Methods for Incorporating Operational Effects

The principal purposes of this workshop session were to:

1. Discuss a systematic highway design process, especially as it relates to operational effects, and concomitantly, to discuss the merits of revising the Green Book to reflect this process; and
2. Discuss the desirability of enhancing the Green Book by incorporating more detail on the operational effects of geometric design.

The seven attendees at this workshop included representatives of state highway agencies, design consultants, and universities.

A systematic highway design process was suggested by Glennon and Harwood a decade ago (1). The authors argue that current design practices are too deterministic. Thus, these practices promote the selection of design parameters based simply on functional classification and design speed. The designer then assumes that he has an acceptable design because he has complied with existing standards. On the other hand, it could be argued this process does not properly account for driver, traffic, vehicle, and environmental variables and will produce a design that may not meet the needs of the drivers.

A systems engineering design emphasizes the total design rather than the design of individual components. If this concept can be applied to highway design, it might be possible to maximize system performance for a given cost. Likewise, the unified design produced with this process would, in theory, provide an environment that meets driver needs.

Workshop participants had varying levels of enthusiasm for this process. Two participants expressed the view that the process was too theoretical and several others had reservations regarding the feasibility of applying systems engineering techniques to highway design. It was suggested that problems with the existing process may, in fact, be due to the following:

- The current process is too compartmentalized. Different individuals are responsible for planning, operations, design, and construction;

- There is confusion regarding the intended application of minimum and desirable design standards. The problem might be alleviated by specifying basic criteria and standards for all roadway types; and

- The Green Book is intended for a new design rather than reconstruction. The application of Green Book techniques to the redesign of existing facilities has a dramatic effect on project costs.

However, participants pointed out that many state highway agencies have their own design manuals. While manuals rely to a considerable extent on the Green Book, they are more responsive to change.

The remaining workshop participants felt that the systematic design process offered some promise and should be pursued. Over half the participants agreed that the highway community should assemble input data on this process. The general consensus was that, if the highway community strongly pursued the implementation of a systematic highway design process, the probability of success would be medium.

If further investigation indicates that this technique is viable, it is appropriate to consider if and how to incorporate into the Green Book. Recognizing that it would require a major overhaul of the Green Book to integrate this technique into the geometric design process, the participants were evenly split in recommending that a discussion of this topic should be in:

- A separate, stand-alone chapter and
- A separate publication.

The second half of this workshop session examined the issue of improving the Green Book by incorporating more detail on the operational effects of geometric design. There are numerous operational examples that could be incorporated into the Green Book. To help focus the discussion, three specific cases were considered:

1. Roadsim: A traffic simulation model for two-lane roads (2);
2. Traffic conflicts on vertical curves (3); and
3. Application of positive guidance techniques (4).

At the beginning of the workshop discussion, the participants were generally familiar with positive guidance, but generally unfamiliar with Roadsim and the modeling of conflicts on vertical curves.

The three sample operational techniques have some basic differences. The Roadsim computer model can help the designer determine the effect of a variety of roadway and traffic conditions. In actual application, the designer would exercise this model to evaluate his proposed design. On the other hand, Farber's computerized simulation model has already been used to predict conflicts near vertical curves. The output consists of a set of tables showing the potential for rear end conflicts with left turning vehicles as a function of roadway and traffic variables. For several years, the traffic engineering community has employed the principles of positive guidance to provide speed and path data compatible with the driver's information processing capabilities. However, a greater appreciation of positive guidance could help engineers correct potential problems through design, rather than through traffic control devices.

In general, the workshop participants supported the idea of incorporating operational techniques in a revised edition of the Green Book. Major issues that should be considered before a particular technique is incorporated include the following:

- Will the readers understand the technique? Any computer model must be properly validated before it is referenced, and even then some may consider the tool to be too research oriented.

- Will designers view a computer model as a black box and therefore, fail to review critically its output?

- How will the technique be included? The most appropriate method will depend on characteristics of the particular technique, including its likely acceptance by the design community, potential for application, and likelihood that it will improve design. An operational technique could be incorporated in the Green Book as (a) an end of chapter reference; (b) a set of general principles; (c) a comprehensive textual discussion; (d) a table, checklist or, figure; (e) a concept integrated throughout the book.

· How will potential techniques be screened? One of the reasons for including selected operational techniques in the Green Book is that designers are not fully aware of these techniques. A cooperative effort between design and operational professionals must occur to ensure that current and valid techniques are included.

· Will the resultant document be too massive? The Green Book is already a large publication. Increasing its size may have some adverse consequences. Also, the existing publication could be streamlined with judicious editing.

The Green Book currently discusses the general principles of positive guidance (pp. 38-49), but not in the detail provided by Post, et al (4); the other two techniques, Roadsim and vertical curve, are not discussed in the Green Book. The workshop participants uniformly agreed there would be significant benefits associated with the application of positive guidance to geometric design. For the other two techniques, the consensus was that their application would be more limited and the potential benefits would be smaller. In general there was a feeling that the additional resources required for the application of the vertical curve and positive guidance techniques would be justified, while there was less certainty about the Roadsim technique. For each of the three techniques, a majority of the participants felt that each technique could be successfully incorporated into a systematic highway design process. The participants consistently felt that all the techniques offered a good opportunity for successful application. However, positive guidance was given the highest probability of success. Finally, there was general agreement that the Green Book should be revised to incorporate more discussion of the techniques of positive guidance, while the other techniques should simply be referenced in the publication.

Conclusion and Recommendations

The workshop session participants had divergent opinions on the applicability of the systematic highway design process. However, they supported further investigation of the issue. The concept of incorporating operational techniques in the Green Book also received support, but the consensus was that individual techniques must be carefully examined to determine if and how they should be included.

References

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Summary of Results

Workshop Session 3A: Opportunities for Updating and Enhancing the Green Book

The workshop session was attended by representatives primarily from transportation agencies. The only exception was a representative from a consulting engineering firm involved in design.

The discussions were open and input was received from all of those present. In general, it was felt that the users did not have any major problems with the Green Book and, in fact, were fairly satisfied with it except the index and cross referencing.

The following is a summary of Workshop Session 3A discussions:

1. Intersection Sight Distance:
   a. Should be further investigated, specifically case III A and B.
   b. Vehicle location needs to be addressed. Will the front of the vehicle be 10' from the edge of the pavement? Maybe it should be closer when shoulders are narrow.

c. Note that in this book, stopping sight distance on the mainline at intersections can be used as a fall back position and still provide a safe facility.
d. Would it be good to combine the "K" value with the charts on pages 798 and 799?

2. Shoulder Widths:
a. Use 8' usable on arterials when design hourly volume (DHV) is greater than 400.
b. Access control should be considered in setting shoulder widths.
c. In urban areas, the width to be provided should be based on speed and volume with no width being specified. If a width is desired, it should be six feet.

3. Speeds:
a. Intermediate areas are properly addressed in the Green Book.
b. The posted speed versus design speed is a problem.
c. All speed definitions should be reviewed.
d. Information should be included in the Green Book on how to measure the existing road for geometrics controlling safe speed.

4. Sight Distance:
a. Height of eyes is a problem.
b. Height of an object is a problem due to visual acuity, practicality, and functional class. Do we need as long a sight distance on a local road as on an arterial for the same design speed?
c. Grade corrections should be addressed in sight distance discussions.
d. Participants in the workshop felt that the 1984 Green Book adequately addressed sight distances on horizontal curves.

5. Other:
a. It was felt that roadside clear zones were adequately covered. Most are happy with the 10 feet dimension on local roads and collectors.
b. Additional information should be added about driveways and it should probably be a separate guide.
c. Superelevation on long downgrades needs to be addressed. For example, is part of the effective superelevation lost when the road curves on a downgrade and should a higher value be used?
d. Research is needed to determine the additional safety provided when spirals are used.
e. The Green Book and the Manual on Uniform Traffic Control Devices (MUTCD) should be made more compatible, especially about passing sight distance and passing zones.
f. The Green Book should have more criteria on traffic control during construction especially considering it also applying to major reconstruction.
g. Warrants for right turn lanes were requested.

Summary of Results

Workshop Session 3B: Opportunities for Updating and Enhancing the Green Book

Topic 1-Intersection Sight Distance

1. Major road:
a. Perception and or reaction time for the driver on a crossroad may be too long.
b. How much will a vehicle on the major road slow down? How is this determined? Should field data be obtained? What is an acceptable speed reduction to assume?
c. Application on reconstruction projects?
d. Low-volume road does not necessarily translate into greater speed reduction. Driver characteristics govern.

2. Trucks:
a. Policy should give guidance on when to use trucks for the various movements.

3. Minimum criteria:
a. Driver behavior seems to dominate.
b. Should stopping sight distance govern for trucks?
c. Green Book should include a statement that the intersection is reasonably safe if the driver on major road has sufficient distance to stop.

4. Height of object and location of eyes:
a. Address the location of driver's eyes, not the bumper.
b. No consensus to lower height of object, but some sentiment for headlight height and for seeing at least 6" of object (In effect, lowering height 6").

General: Green Book should outline how these decisions are to be made.

Topic 2-Shoulder Width

1. Rural:
a. Need a better definition or a better understanding of the definition. The problem is not so much in roadway design as in determining what width is required to carry across bridges.

b. Investigate widths based on factors other that average daily traffic, such as Human Factors.
c. No support for 10' shoulder width on two-lane rural roadways.

2. Urban:
a. Need interpretation on border width in curb and gutter section. Measured from lip, face or back of curb?
b. Keep urban shoulder policy flexible.

Topic 3-Design Speed

1. Definition needs to be clarified. No confidence in running speed as defined in Green Book.
2. More guidance needed on selecting design speed for specific conditions.
3. Relationship between design and posted speed is a problem on reconstruction projects.
4. Guidance only on selecting design speed of existing highways. Refer to existing methods.
5. Relationship between design and running speed should be revised. Minimums are being used. Suggested that instead of desirable and minimum, new construction and reconstruction be used.

Topic 4-Stopping Sight Distance

1. Height of eyes and height of object:
a. All the studies are fine as long as any changes apply to new construction only.
b. The economic effects on reconstruction-type projects of any changes are severe.

2. Grade correction:
a. Should be considered.
b. No real need to change policy.

3. Horizontal Curves:
a. Major problem is the economics of reconstruction projects.
b. Other issues adequately covered.

General: Research for stopping distance should be into areas other than braking.

Topic 5-Roadside Clear Zones

1. Roadside policy and guide should be kept flexible. It is not being interpreted that way.

2. Low-speed rural roads. Flexibility is even more important.

3. Urban 1.5 feet clearance is acceptable as is.

General: A thorough study of the safety versus economic trade-offs is needed.

Topic 6-Driveways

1. Would like guidance in the Green Book, but not specifics of spacing and location.

2. Guidance on selecting the design vehicle.

Other Topics

1. Detour design should be discussed.

2. No consensus on what the Green Book should be; guide, policy, design manual or what?

Conclusions

Although the issues drawing the most discussion were stopping sight distance and intersection sight distance, in almost every discussion on every issue, the primary concern was the economics of reconstruction-type projects. For this reason, an item, "Cost Effectiveness as a Design Issue" was added to the evaluation (along with detour design). The cost-effectiveness issue did not finish near the top of the evaluation; however, it is the moderator's opinion that cost is the underlying factor in at least three of the four topics rated higher on the evaluation. From listening to the discussions, it is my conclusion that Green Book users are as much concerned about the cost effects of the proposed changes than they are about the theoretical correctness of the numbers.

Recommendation

1. To remain usable over the long run, the Green Book must address economic trade-offs in some manner, probably along the lines of *Special Report 214: Designing Safer Roads: Practices for Resurfacing, Restoration and Rehabilitation*. How this can be accomplished will become a major issue for AASHTO leadership.

Summary of Results

Workshop Session 4A: Geometric Design Research

The workshop was conducted in a fairly structured manner. Five candidate research topics were identified before the workshop to provide some frame work for the discussion. These were:

1. Intersection sight distance,
2. Stopping sight distance,
3. Reduced lane or shoulder width on urban freeways,
4. Relationship between geometric design elements and traffic control devices, and
5. Relationship between accidents and geometric design.

Each of these topics were addressed by the group. The overall need for research in these areas was discussed as well as specific research topics with these general topic areas. The members of the panel also numerically evaluated each research topic. The results of that evaluation are provided at the end of this report. The following is a review of the findings of the workshop about geometric design research needs.

Intersection Sight Distance

This topic did not appear to generate significant interest on the part of the workshop panel. The panel did discuss the lack of consideration for low volume intersections in the intersection sight distance section of the Green Book and the difficulty and cost of meeting the standard sight distance criteria at these low volume intersections.

In a related topic, the panel noted that there is no variation allowed in design vehicle acceleration characteristics. This could be important for some low volume rural intersections where the design vehicle might more reasonably be a pickup truck.

The panel also discussed the need for an improved perception-reaction time value for use in calculating intersection sight distance. A FHWA study, developed a more realistic value for perception-reaction time for use in intersection sight distance.

Stopping Sight Distance

This topic generated more discussion on the part of the workshop group then did intersection sight distance. The major concern was the application of the stopping sight distance criteria, or more importantly, the revised criteria recommended in the National Cooperative Highway Research Program (NCHRP) *Report 270: Parameters Affecting Stopping sight Distance* (2) concerning existing crest vertical curves under the Resurfacing, Restoration and Rehabilitation (3R) Program.

There was general agreement that the actual safety effects of various crest vertical curve designs are necessary for developing cost-effective crest vertical curve design procedures but are not currently available. The group was informed that the Texas Transportation Institute was conducting a study to do just that for the State of Texas.

Concern was also expressed that the current procedure does not consider what portion of a crest vertical curve has inadequate sight distance. The panel believed that this issue would be critical, if research is initiated to examine crest vertical curve sight distance from a cost-effectiveness point of view.

Another issue related to stopping sight distance was object recognition. One of the presentations in the conference indicated the limits of stopping sight distance may well be when a driver recognizes an object so that he or she can react to it. If a sight distance is called for and provided, that a driver cannot practically use, then object recognition distance may become a limiting factor in stopping sight distance calculations. The panel thought this issue should be pursued in research.

Reduced Lane Width and Shoulder Width on Urban Freeways

This topic generated some interesting discussion. While everyone agreed the importance of this topic is growing as more urban areas deal with capacity problems on their freeways, some panel members felt research had already been conducted which indicated reducing lane width and shoulder width to add a lane posed no serious safety problems. The discussion spread from the specific issue of adding an additional lane through lane and shoulder narrowing, to the more general topic of the relative safety of various lane and shoulder widths and the need for and safety of left shoulders.

The panel felt that since there was apparently a body of research on this topic, a synthesis of existing research in this area would be productive.

It was also noted that the Green Book already had allowances for lane narrowing. The panel felt what was needed was some guidance on when lane narrowing was appropriate.

Relationship Between Geometric Design Elements and Traffic Control Devices

This topic did not generate great interest on the part of the panel. The one area of discussion centered on the relationship between operating speed, posted speed, and design speed. This is especially important in urban areas where there is often insufficient right of way for a design based on a reasonable design speed. Often, an artificially low design speed is selected for these situations which has little relationship to the posted speed or the operating speed of the highway in question. It was felt that some rational process for predicting the operating speed of a highway was needed for use in selecting an appropriate design speed.

There was also a discussion of the need to consider the possibility of future ramp metering or high occupancy lanes in the design of interchanges. Currently, no information or guidance is available for making such considerations.

Relationship Between Accidents and Geometric Design

The discussion of this topic was based on the recommendation of the Transportation Research Board's report on Standards for 3R Projects that research was needed to quantify the relationship between various geometric design elements and relative safety. Such information could be used to generate more cost-effective geometric design criteria for 3R projects.

The workshop group generally agreed such information would be valuable. They further agreed this was high-risk research, that is, expensive with a low probability of success, and therefore should be conducted on a fairly selective basis.

Other Topics

The panel discussed some other issues related to the Green Book which, while not necessarily requiring research are of interest. One issue is the apparent mix of philosophies within the Green Book. On the one hand, a worst case is assumed in some parts of the Green Book, for example, braking distances on wet pavements with bald tires, while elsewhere average conditions are used, such as average eye height. There was also considerable discussion about the need for more urban guidance in the Green Book.

Implementation of Research Results

The workshop also discussed, as directed, problems and issues related to the implementation of geometric design research. One problem also noted in the general session was the general unavailability of FHWA reports. It was suggested that, at a minimum, FHWA should regularly maintain the R&D Report Index so users can at least determine what reports are available through the National Technical Information Service. There was also some discussion of the need for critical syntheses of research in particular areas to help policy makers determine the quality and general applicability of individual research efforts.

Research Problem Evaluations

As noted earlier, the workshop panel was asked to evaluate numerically the individual research problem areas discussed. These problem areas were given scores based on the importance of pursuing research in the area. These scores were compiled and evaluated in two ways: The highest total score, and most scores of 8 or greater (based on a score of 0 to 10). The results were similar in both cases, although, the rankings of the panel did not necessarily reflect the interest shown during the discussions. Stopping sight distance, and reduced lane and shoulder width were the two highest ranking problem areas. Intersection Sight Distance was also ranked fairly high. Little interest was indicated in the Relationship Between Geometric Design and Traffic Control Devices, or the Relationship Between Geometric Design and Accidents.

Summary of Results

Workshop Session 4B: Geometric Design Research

Five topics initiated our discussion; however, without any difficulty the group developed an additional six topics of their own and there was a lively discussion of all of these.

As a final result of the group's evaluation, these eleven topics were ranked in the following order:

1. Overview of the Sight Distance Model,
2. Integration of Research Results into AASHTO Geometric Policy,
3. Stopping Sight Distance,
4. Litigation Problems,

5. Integration Geometric Design Elements and Traffic Control Devices,
6. Roadside Design Elements,
7. Reduced Lanes and or Shoulder Widths on Urban Freeways,
8. Relationship Between Accidents and Geometric Design,
9. Expert Systems to Relate Geometrics and Traffic and compare MUTCD,
10. Intersection Sight Distance, and
11. Left Turn Lane Warrants.

A review of the various organizations involved in this particular work sessions includes the following:

State and municipal agencies 3
Research consultants 3
University or academic 4
Federal 4
Other (general) 1

There were several more persons in the session for at least a portion of it; however, they did not have the opportunity to fill out an evaluation form or did not take the opportunity to do so.

The two subjects that apparently received the most discussion or had the greatest effect were as follows:

1. Change the procedure for design policy development for the Green Book. Allow it to be more open to professional groups and those who are more directly connected to the use of those policies; or for instance, those that are in the field doing the design work.
2. Change the procedure for updating policy related to design, to commit the appropriate staff and more importantly the appropriate funding. This should be a continuing process, not a one-step process as was this workshop.

With reference to the first, the group felt very strongly that AASHTO did not seek the input of those professional groups most connected to the use of geometric design policies.

It was further suggested that the procedures and research used to revise this Highway Capacity Manual should be considered as a method for updating the Green Book.

Also, when the HCM was developed, those responsible for developing this manual had reviews throughout the nation to make the information available to as many groups as possible and to receive their input before putting the manual into its final form.

References

1. *Special Report 214: Designing safer Roads: Practices for Resurfacing, Restoration and Rehabilitation*. TRB, National Research Council, Washington, D.C., 1987.

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PART 2B: WORKSHOP SESSIONS

WORKSHOP SESSION #1

TOOLS AND TECHNIQUES TO REFLECT OPERATIONAL EFFECTS IN THE DESIGN PROCESS

Focus

The primary focus of Workshop #1 was:

1. to discuss the prevalent design process in the United States and how it might be improved;
2. to identify and discuss existing and needed tools and techniques to reflect the operational effects of geometric design; and
3. to discuss how and where these operational techniques might be integrated into the design process.

Issues

1. *The Design Process*. The Workshop attendees discussed the design process, including:
   a. the prevalent design environment today, in which each design element is addressed individually; and
   b. an alternative design process, in which an optimum geometric design is determined by a systematic approach which incorporates 1) the operational effects of geometrics and 2) the combined impact of geometric design elements working in unison with the driver and vehicles.

To provide a frame of reference, an abstract was prepared to describe a systematic approach to highway design. An evaluation form was prepared for each attendee to complete after the Workshop discussion.

2. *Existing Operational Techniques*. Many operational techniques have been documented in the highway literature. Because of time constraints, the Workshop attendees discussed three existing operational techniques which have been developed. All three are related to geometric design consistency--a concept which has gained considerable attention from the highway design community in recent years. Most agree that a consistent geometric design is conducive to highway safety and driver comfort. However, designers may find value in techniques which can quantify the level of consistency within a highway section. Therefore, these techniques were discussed:
   a. geometric design consistency related to driver expectancy,
   b. operating speed profiles (Leisch method), and
   c. operating speed profiles (German method).

Abstracts were prepared to discuss each operational technique and to help guide the discussion. An evaluation form was prepared for each technique for the attendees to complete after the Workshop discussion.

3. *Needed Operational Techniques*. The existing bank of operational tools and techniques do not address all needs. The Workshop attendees identified other tools and techniques which are needed to reflect the operational effects of geometrics. For instance an attendee may have recognized a need to evaluate an operational effect, but was without any formal, documented technique to do so. Therefore, the Workshop discussed areas where operational tools and techniques are needed.

WORKSHOP SESSIONS #1 AND #2

Abstract

Title: ***Systematic Approach to Highway Design***
Source: ***Highway Design Consistency and Systematic Design Related to Highway Safety," Transportation Research Record 681***

Description of Basic Concepts: The prevalent highway design environment in the United States has been described as deterministic. This implies that highway features are designed according to a set of design criteria for individual design elements. For example, a crest vertical curve is designed to provide at least stopping sight distance to a 6-inch object for a selected design speed. However, many other factors may influence the safety and operations of the curve. These include traffic volumes, percentage of trucks, lane/shoulder widths, driver familiarity with the highway, present and future pavement friction, level of roadside development, presence of intersections and horizontal alignment. These factors are certainly considered in today's highway design process, but the evaluation is often subjective rather than objective.

An alternative approach may be to develop a systematic design process and to determine the most probably interrelationships between geometric design and other factors (e.g., traffic volume and mix, driver characteristics, other geometric features). Potentially, this process could yield a geometric design which more closely matches the specific conditions within a highway segment. Figure 1 illustrates one example of a systematic highway design process. The following presents the few key elements of the process:

1. *Systems Engineering Approach*. This may be defined as a form of problem solving that emphasizes the total design rather than the design of the individual parts. The objective is to maximize system performance for a given cost or to minimize cost for a given performance. This concept may be applicable to the highway design process to, yield theoretically, an optimum design.
2. *Combined Impact of Design Elements*. One key feature of a systematic highway design process is to recognize that, in practice, the highway design elements function in unison to create an overall operational environment. With the proper input data, a systematic design process can incorporate this factor into the final highway design.
3. *Measures of Performance*. A systematic design process requires the development of objective performance measures. These are needed for each design element and type of highway facility. Performance measures would be based on traffic volumes, traffic composition, expected driver performance on that highway facility, etc.
4. *Cost Effectiveness Methodology*. A cost-effectiveness model is an integral part of a systematic highway design process. This can objectively evaluate the trade-offs between alternative highway designs. With the proper input data, an optimum design can be selected which finds the balance between the benefits of highway design improvements and the costs to attain these improvements.

WORKSHOP SESSION #1, Abstract #1

Title: ***Highway Geometric Design Consistency Related to Driver Expectancy***
Source: FHWA/RD-81/035/036/037/038

Description of Basic Approach: The report examines the factors which determine the geometric design consistency of a proposed or existing rural highway. The driver workload demand should be consistent with the experiences and capacity of a "typical" driver to react to the highway environment. Where the workload demand significantly exceeds the driver's capacity, the technique will identify a geometric inconsistency which can result in undesirable driver reaction. As an alternative expression, the driver may be "surprised" by the geometric inconsistency based on his/her expectancies. These expectancies result from both long-term memory (many years of driving exposure) and short-term memory (immediate experiences on the highway before encountering the geometric inconsistency).

Description of Technique: The report presents a step-by-step procedure to calculate the driver workload for a specific geometric design feature or combination of features. This value is then compared to a suggested scale which ranges from "No Problem Expected" to "Major Problem Possible." The calculated driver workload reflects several factors:

1. the nature of the geometric feature (e.g., horizontal curve, narrow bridge, intersection),
2. the 85th percentile speed,
3. the available sight distance to the feature,
4. level of driver unfamiliarity.

Potential Application: The designer will use the technique to determine the geometric design consistency on a rural highway project. The designer will be able to identify specific geometric features or combinations of features which may create a serious driver workload problem. He/she will then be able to identify selectively corrective actions (e.g., flatten a horizontal curve) which should yield commensurate benefits in driver safety and comfort.

WORKSHOP SESSION #1, Abstract #2

Title: ***New Concepts in Design Speed Application (Leisch Method)***
Source: Transportation Research Record 631, Pages 4-14

Description of Basic Approach: The application of a single design speed to highway geometric design can result in large variations of actual speeds within the highway segment. Drivers may increase speeds on tangent sections to a considerably higher level than the design speed of an approaching horizontal curve. This is especially true on highways with lower design speeds. In addition, the speed differential between a passenger car and truck at the same point should not be so great that operational or safety problems will develop.

A more desirable objective is to provide a geometric design which produces a uniform operating speed throughout a highway segment. This can be

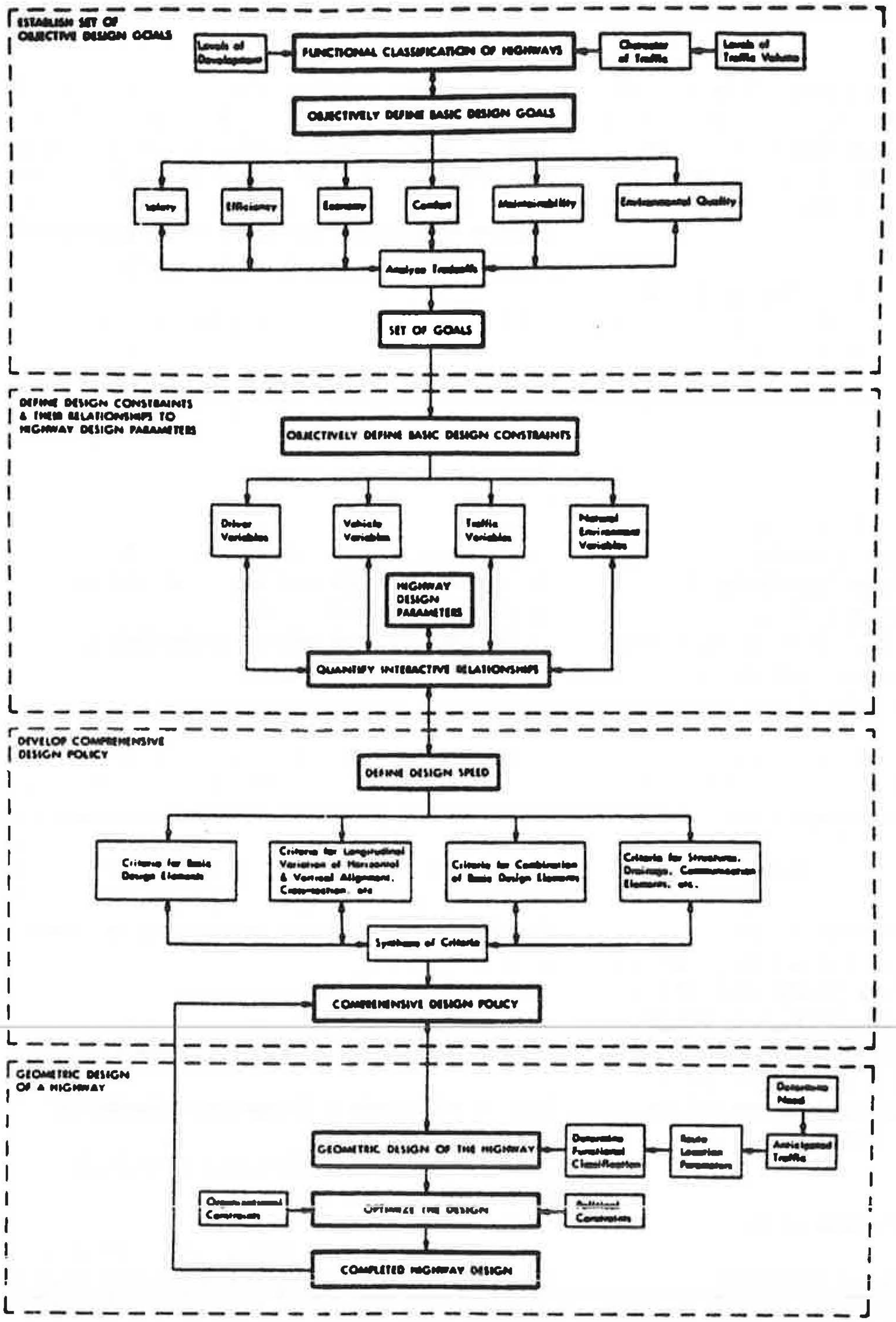

FIGURE 1 Systematic highway design process.

accomplished by discouraging higher speeds to lower speed significantly, or by a combination of the two. The result will be a geometric design which promotes a uniform travel speed which will provide benefits to driver safety and comfort.

Description of Technique: The paper presents a step-by-step procedure to construct a design speed profile for a proposed or existing highway design. The objective is to identify any geometric feature which result in a speed variance of more than 10 mph for a passenger car. The speed differential between a passenger car and truck at the same highway feature (e.g., a continuous grade) should not exceed 15 mph. (Note: The Green Book now recommends that this value should not exceed 10 mph). The design speed profile reflects many operational factors:

1. typical top speeds on tangent sections based on highway classification,
2. acceleration/declaration characteristics of passenger cars and trucks,
3. separate profiles for cars and trucks, and
4. typical operating speeds for specific geometric design features (horizontal curves, vertical curves and grades).

Potential Application: The designer will use the technique to evaluate the consistency of the highway geometric design. It will identify specific geometric features or combinations of features which produce undesirable variations in speeds. This can lead to geometric improvements which will promote a relatively uniform operating speed throughout a significant length of a highway segment.

WORKSHOP SESSION #1, Abstract #3

Title: *Comparison of Different Procedures for Evaluating Speed Consistency*
Source: *Transportation Research Record 1100*, Pages 10-20

Note: The paper compares three techniques to evaluate speed consistency (Leisch, Swiss and German methods). This abstract describes the German method, called the "curvature change rate."

Description of Basic Approach: Abrupt changes in horizontal alignment within a highway segment can result in undesirable operating conditions. Field observations in Germany have discovered that actual operating speeds are positively correlated with a parameter called the "curvature change rate" (CCR). CCR is defined as the sum of the angular changes (absolute values) in the horizontal alignment divided by the length of the highway section. The objective is to ensure that the operating speed will be relatively close to the design speed as determined by the most restrictive horizontal curve within the highway section. This will promote a uniform operating speed which will be consistent with the principles of driver safety and comfort.

Description of Technique: The paper present a procedure and charts to calculate and compare the CCR within a highway section. The section is divided into subsections which have a relatively homogeneous horizontal alignment. The CCR is then calculated for each subsection. These values will yield predicted operating speeds for various lane widths for the successive highway subsections. If the differences in the operating speeds exceed the recommended limits, then a speed inconsistency has been identified. The German limits are approximately 6 mph. In the United States, 10 mph is a more common threshold.

Potential Application: The designer will use the CCR technique to evaluate the horizontal alignment of an existing or proposed highway design. It will predict the actual operating speeds of successive highway sections based on field studies which have correlated the CCR to actual speeds. If a speed inconsistency is identified by the technique, the designer can make improvements to the horizontal alignment which will promote a uniform operating speed throughout the highway section.

EVALUATION
SYSTEMATIC APPROACH TO HIGHWAY DESIGN

1. Please check the appropriate box for whom you represent:

- ☐ State transportation/highway agency
- ☐ Federal agency
- ☐ Research consultant
- ☐ Design consultant
- ☐ Other ____________________

2. How would you evaluate the prevalent highway design process in the United States?

- ☐ Not seriously flawed; usually results in a highway design which is compatible with its operation environment.
- ☐ Needs improvement but performs adequately.
- ☐ Is seriously flawed and needs a major overhaul.

Other comments

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3. How would you evaluate the applicability of a systematic highway design process?

- ☐ Appears to be very promising and should be pursued vigorously by the highway design community.
- ☐ Appears to have some merit and may warrant further investigation.
- ☐ Some aspects appear promising and these should be incorporated into the existing highway design process.
- ☐ Appears to be theoretically sound but is unlikely to work in practice.
- ☐ Appears to have little or no practical value.

Other comments

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4. Should the highway community embark on a major research effort to gather the necessary input data for a systematic highway design process?

☐ Yes

☐ No

☐ Not sure

5. The highway design community could strongly pursue the implementation of a systematic approach to highway design. How would you characterize the probability of success?

☐ High

☐ Medium

☐ Low

☐ None

6. Please provide any other comments.

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WORKSHOP SESSION #1, EVALUATION

Operational Techniques (Geometric Design Consistency)

A matrix is included at the end of this evaluation form. Please complete the matrix with your response to the following questions for each technique.

I. How would you describe your familiarity with and usage of the operational technique before this Workshop?

A. Never heard of technique.
B. Have heard of technique but never read report/paper.
C. Have read the report/paper, but have never applied.
D. Have read the report/paper and have applied it to further research.
E. Have read the report/paper and have applied it to a highway design project.

II. Either based on experience or based on a perceived application, how would you describe the potential benefit of the operational technique to the geometric design?

A. Can be applied to all projects with significant benefits.
B. Can be applied selectively to projects with significant benefits.
C. Can be applied to some projects with perhaps a small benefit.
D. It is unlikely to be successfully applied to a significant number of projects.
E. Technique appears to have no practical value.

III. Each application of the technique to a project will require an expenditure of time and engineering resources by the user agency. Therefore, a commensurate benefit must be attained. In your opinion, will the final highway design using the operational tool be improved (when compared to the design without the technique) sufficiently to justify the additional resources?

A. Definitely yes
B. Probably yes
C. Not sure
D. Probably not
E. Definitely not

IV. In your opinion, can the operational technique be successfully integrated into:

A. the exiting highway design process
B. a systematic highway design process
C. either of the above
D. neither of the above

If A, B, or C is selected, please indicate in the "comments" section where the technique could best be applied in the design process.

V. The highway design community could strongly pursue the application of the technique on a wide-spread basis. How would you characterize the probability of success?

A. High
B. Medium
C. Low
D. None

WORKSHOP SESSION #1

EVALUATION OF OPERATIONAL TECHNIQUES

Please check the appropriate box:

- ☐ State transportation/highway agency
- ☐ Federal agency
- ☐ Research consultant
- ☐ Design consultant
- ☐ Other ______________________

Operational Technique	Question				
	I	II	III	IV	V
#1 Highway Geometric Design Consistency					
#2 Design Speed Profile (Leisch)					
#3 Curvature Change Rate (German)					
#4					
#5					
#6					

Please provide any comments you have on any of the operational techniques:

#1 "Highway Geometric Design Consistency"

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#2 "Design Speed Profile (Leisch)"

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#3 "Curvature Change Rate (German)"

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WORKSHOP SESSION #2

METHODS FOR INCORPORATING OPERATIONAL EFFECTS

Focus

The primary focus of Workshop #2 was:

1. to discuss a systematic highway design process and to discuss techniques to reflect the operational effects of geometric design;
2. to discuss the desirability for recommending that the Green Book be enhanced to reflect a systematic design process; and
3. to discuss the desirability of recommending that the Green Book be enhanced to better reflect the operational effects of geometrics.

Issues

1. *The Design Process*. The Workshop attendees discussed the design process. This included:

a. the prevalent design environment today, in which each design element is addressed individually; and
b. an alternative design process, in which an optimum geometric design is determined by a systematic approach which incorporates 1) the operational effects of geometrics and 2) the combined impact of geometric design elements working in unison with the driver and vehicle.

To provide a frame of references, an abstract was prepared to describe a systematic approach to highway design. After discussion of the advantages and disadvantages of a systematic design process, the Workshop discussed the desirability of modifying the Green Book to incorporate some or all of its features. An evaluation form was prepared for each attendee to complete after the Workshop discussion.

2. *Operational Techniques*. Many operational techniques have been documented in the highway literature. Because of time constraints, the Workshop attendees discussed three existing operational techniques which have been developed. These were:

a. two-lane traffic simulation (Roadsim),
b. modeling conflicts at intersections hidden by vertical curves, and
c. positive guidance.

Abstracts were prepared to discuss each operational technique and to help guide the discussion. The objective was to gain an overall insight into the practicality of operational techniques. After the discussion on these three examples, the Workshop discussed the desirability of modifying the Green Book to incorporate various techniques. An evaluation form was prepared for each technique for the attendees to complete after the Workshop discussion.

WORKSHOP SESSIONS #1 AND #2

Abstract

Title: ***Systematic Approach to Highway Design***
Source: ***Highway Design Consistency and Systematic Design Related to Highway Safety, Transportation Research Record 681***

Description of Basic Concepts: The prevalent highway design environment in the United States has been described as deterministic. This implies that highway features are designed according to a set of design criteria for individual design elements. For example, a crest vertical curve is designed to provide at least stopping sight distance to a 6-inch object for a selected design speed. However, many other factors may influence the safety and operations of the curve. These include traffic volumes, percentage of trucks, lane/shoulder widths, driver familiarity with the highway, present and future pavement fraction level of roadside development, presence of intersections and horizontal alignment. These factors are certainly considered in today's highway design proces, but the evaluation is often subjective rather than objective.

An alternative approach may be to develop a systematic design process and to determine the most probable interrelationships between geometric design and other factors (e.g., traffic volume and mix, driver characteristics, other geometric features). Potentially, this proces could yield a geometric design which more closely matches the specific conditions within a highway segment. Figure 1 illustrates one example of a systematic highway design process. The following presents the few key elements of the process:

1. *Systems Engineering Approach*. This may be defined a form of problem solving that emphasizes the total design rather than the design of the individual parts. The objective is to maximize system performance for a given cost or to minimize cost for a given performance. This concept may apply to the highway design process to, yield theoretically, an optimum design.

2. *Combined Impact of Design Elements*. One key feature of a systematic highway design process is to recognize that, in practice, the highway design elements function in unison to create an overall operational environment. With the proper input data, a systematic design process can incorporate this factor into the final highway design.
3. *Measures of Performance*. A systematic design process requires the development of objective performance measures. These are needed for each design element and type of highway facility. Performance measures would be based on traffic volumes, traffic composition, expected driver performance on that highway facility, etc.
4. *Cost-Effectiveness Methodology*. A cost-effectiveness model is an integral part of a systematic highway design process. This can objectively evaluate the tradeoffs between alternative highway designs. With the proper input data, an optimum design can be selected which finds the balance between the benefits of highway design improvements and the costs to attain these improvements.

WORKSHOP SESSION #2, Abstract #1

Title: ***Two-Lane Traffic Simulation: A Field Evaluation of Roadsim***
Source: ***Transportation Research Record 1100***

Description of Basic Approach: The paper describes the field validation of Roadsim--a traffic simulation model for two-lane rural roads. The model was developed by FHWA in 1980 to allow simulation analyses of operating conditions on these facilities. The objective is to determine the impact of various roadway and traffic conditions on an array of measures of effectiveness (MOE's) the MOE's generated by Roadsim include mean travel speed, average delay, headway distributions and distribution of platoon sizes. These are all indications of serviceability of the two-lane highway.

The field validation study indicated that Roadsim's simulation results compared favorably with those observed in the field. This was based on statistical analyses of the data. This indicates that Roadsim, with further evaluation and enhancements, will be a useful tool to evaluate the operational effects of geometrics on two-lane rural highways.

Description of Technique: Roadsim analyzes the operational impact of various traffic and geometric parameters for a specific highway segment. These include:

1. horizontal curve data,
2. vertical curve data,
3. grades,
4. passing sight distance,
5. free-flow speed (analogous to design speed),
6. traffic volumes,
7. vehicular composition, and
8. vehicular performance characteristics.

Based on the input data, Roadsim will generate data on the various MOE's. This includes platooning data, which is one method of measuring the level of service of rural two-lane highways. A sensitivity analysis of various horizontal and vertical alignment characteristics determined that horizontal curves with radii less than 1500 feet and grades of 3% or more had a significant impact on mean travel speeds.

Potential Application: Simulation allows the designer to evaluate the impacts of several alternative approaches. With Roadsim, a designer can vary the geometrics of a highway segment and, for a given set of traffic conditions, can predict the operational impact of each alternative.

WORKSHOP SESSION #2, Abstract #2

Title: ***Modeling Conflicts at Intersections Hidden by Vertical Curves***
Source: Paper presented at 1987 TRB Annual Meeting

Description of Basic Approach: An intersection or driveway just beyond a crest vertical curve on a two-lane highway can create a hazardous condition. The paper presents a technique which simulates the operating conditions and, based on the input criteria, predicts the number of potential conflicts at the crest vertical curve. A conflict is identified when a vehicle is stopped to turn left at an intersection or driveway, a following driver does not observe the slowing down of the turning vehicle (i.e., no advance warning), and there is inadequate (or marginal) sight distance for the following vehicle to stop in time to avoid hitting the stopped vehicle. The number of conflicts predicted by the simulation model cannot be directly converted into a predicted number of accidents. However, it will provide a quantifiable means to estimate the hazard at a crest vertical curve and to evaluate the benefits or proposed countermeasures.

Design of Technique: The report describes the model which simulates the operating conditions at an intersection just beyond a crest vertical curve. Many variables will determine the predicted number of conflicts, and these are reflected in the simulation model. They include:

1. traffic volumes
2. headway distributions in both directions of travel,
3. driver left-turn gap acceptance,
4. pavement friction,
5. vertical curve geometry,
6. driver eye and object height,
7. typical driver reaction times, and
8. speeds of approaching (following) vehicles.

Potential Application: The model has been developed to allow site-specific input data. Therefore, the number of conflicts can be predicted for any intersection on a two-lane highway beyond a crest vertical curve. In addition, the simulation capability allows the designer to evaluate the benefits (reduced number of conflict) for a given countermeasure. For example, improved pavement friction and/or improved curve geometrics will reduce the number of conflicts.

WORKSHOP SESSION #2, Abstract #3

Title: ***A User's Guide to Positive Guidance (Second Edition)***
Source: FHWA-TO-81-1

Description of Basic Approach: The concept of positive guidance has existed for at least 15 years. It is an engineering tool designed to enhance the safety and operational efficiency of hazardous locations. Positive guidance combines engineering and human factors technologies to produce a highway information system which is compatible with the driver's information processing characteristics. The intent is to avoid highway system failures, which may range from a traffic delay or lost driver to a fatal accident.

Positive guidance incorporates the attribute of driver psychology. Drivers constantly receive and process information as they drive. Several factors are significant. One is that drivers establish a hierarchy of information importance--some information is more crucial to the driving task than others. Second, drivers have developed an expectancy based on their previous driving experience. Third, drivers are limited in the amount of information they can process and react to comfortably in a given time frame. All of these should be considered in highway design.

Description of Technique: The User's Guide presents a step-by-step procedure to apply the positive guidance concept to individual sites. The key elements of the procedure are to:

1. identify the nature of the hazard,
2. determine the information processing at the site,
3. identify violations of driver expectancy,
4. evaluate driver information loads,
5. evaluate existing information systems, and
6. develop a positive guidance plan to correct the hazard.

Potential Application: The User's Guide emphasizes the use of traffic control devices to correct hazards identified by the positive guidance technique. However, the concept can also be used to implement geometric design improvements. Geometric design is a significant factor in the driver information processing system, and it is more desirable to correct physically the hazard than to only warn the driver of the hazard. Therefore, the highway designer will use the positive guidance technique to identify cost-effective geometric design improvements or to work with traffic engineers to ensure that geometric design considerations are properly reflected in its evaluation and application.

EVALUATION
SYSTEMATIC APPROACH TO HIGHWAY DESIGN

1. Please check the appropriate box for whom you represent:

- ☐ State transportation/highway agency
- ☐ Federal agency
- ☐ Research consultant
- ☐ Design consultant
- ☐ Other ______________________________

2. How would you evaluate the prevalent highway design process in the United States?

- ☐ Not seriously flawed; usually results in a highway design which is compatible with its operational environment.
- ☐ Needs improvement but performs adequately.
- ☐ Is seriously flawed and needs a major overhaul.

Other comments

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3. How would you evaluate the applicability of a systematic highway design process?

- ☐ Appears to be very promising and should be pursued vigorously by the highway design community.
- ☐ Some aspects appear promising and these should be incorporated into the existing highway design process.
- ☐ Appears to be theoretically sound but is unlikely to work in practice.
- ☐ Appears to have little or no practical value.

Other comments

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4. Should the highway community embark on a major research effort to gather the necessary input data for a systematic highway design process?

- [ ] Yes
- [ ] No
- [ ] Not sure

5. The highway design community could strongly pursue the immplementation of a systematic approach to highway design. How would you characterize the probability of success?

- [ ] High
- [ ] Medium
- [ ] Low
- [ ] None

6. The Green Book could be revised to discuss a systematic higheway design process. In your opinion, should this workshop recommend to AASHTO:

- [ ] a major overhaul of the Green Book to integrate fully the systematic design process into geometric design
- [ ] a separate, stand-alone chapter which would describe and encourage a systematic design process
- [ ] a separate publication from the Green Book to describe the systematic design process
- [ ] no action is warranted.

7. Please provide any other comments.

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WORKSHOP SESSION #2, EVALUATION

Operational Techniques

A matrix is included at the end of this evaluation form. Please complete the matrix with your response to the following questions for each technique.

I. How would you describe your familiarity with and usage of the operational technique before this Workshop?

A. Never head of technique.
B. Have heard of technique but never read report/paper.
C. Have read the report/paper, but have never applied.
D. Have read the report/paper and have applied it to further research.
E. Have read the report/paper and have applied it to a highway design project.

II. Either based on experience or based on a perceived application, how would you describe the potential benefits of the operational technique to geometric design?

A. Can be applied to all projects with significant benefits
B. Can be applied selectively to projects with significant benefits
C. Can be applied to some projects with perhaps a small benefit
D. It is unlikely to be successfully applied to a significant number of projects
E. Technique appears to have no practical value

III. Each application of the technique to a project will require an expenditure of time and engineering resources by the user agency. Therefore, a commensurate benefit must be attained. In your opinion, will the final highway design using the operational tool be improved (when compared to the design without the technique) sufficiently to justify the additional resources?

A. Definitely yes
B. Probably yes
C. Not sure
D. Probably not
E. Definitely not

IV. In your opinion, can the operational technique be successfully integrated into:

A. the existing highway design process
B. a systematic highway design process
C. either of the above
D. neither of the above

If A, B, or C is selected, please indicate in the "comments" section where the technique could best be applied in the design process.

V. The highway design community could strongly pursue the application of the technique on a wide-spread basis. How would you characterize the probability of success?

A. High
B. Medium
C. Low
D. None

VI. The Green Book could be revised to discuss the operational technique. In your opinion, should this workshop recommend to AASHTO:

A. a revision of the Green Book to incorporate the technique
B. a reference in the Green Book to the technique
C. a separate publication to present this and other operational techniques
D. no action is warranted

WORKSHOP SESSION #2

EVALUATION OF OPERATIONAL TECHNIQUES

Please check the appropriate box:

- ☐ State transportation/highway agency
- ☐ Federal agency
- ☐ Research consultant
- ☐ Design consultant
- ☐ Other ______________________

Operational Technique	Question					
	I	II	III	IV	V	VI
#1 Two-Lane Traffic Simulation (Roadsim)						
#2 Modeling Conflicts at Vertical Curves						
#3 Positive Guidance Application						
#4						
#5						
#6						

Please provide any comments you have on any of the operational techniques:

#1 "Two-Lane Traffic Simulation (Roadsim)"

#2 "Modeling Conflicts at Vertical Curves"

#3 "Positive Guidance Application"

#4

#5

#6

WORKSHOP SESSION #3

OPPORTUNITIES FOR UPDATING AND ENHANCING THE GREEN BOOK

Focus

The primary focus of Workshop #3 was to identify opportunities for updating and enhancing the Green Book. These were based on user experience with the publication. After a discussion of the issues, the Workshop attendees evaluated the issues according to their relative importance.

Prepared Issues

There are many candidate issues which could have been addressed in this Workshop, and all participants were encouraged to express their views. However, to provide some framework for discussion, six topics were identified for initial discussion:

1. intersection sight distance,
2. shoulder widths,
3. design speed,
4. application of stopping sight distance,
5. roadside clear zones, and
6. driveway design.

A brief discussion was prepared on each topic, and a few relevant observations were made. By no means were those observations considered all inclusive; they were intended to initiate the dialogue. The observations lead to other aspects of the topic which merited discussion.

Note that the list of prepared issues does not include some potential changes in the Green Book which are well recognized in the highway design community. For example, the AASHTO Task Force on Geometric Design is evaluating geometric design considerations related to the large trucks allowed by the 1982 STAA. In addition, future editions of the Green Book will likely reflect changes resulting from the 1985 *Highway Capacity Manual*.

Open Discussion

After discussion of the prepared issues, the Workshop opened to any issues which the participants believed merited discussion. These were related to specific issues (e.g., the two-way, left-turn lane) or general issues (Green Book should be more or less specific).

Evaluation

After a discussion of all issues presented, the Workshop attendees evaluated each topic on a scale of 0 to 10. The objective was to provide a relative indication of the overall value of pursuing the issue in future updates of the Green Book.

WORKSHOP SESSION #3: Discussion Topics

Topic #	Title
1.	Intersection Sight Distance
2.	Shoulder Widths
3.	Design Speed
4.	Application of Stopping Sight Distance
5.	Roadside Clear Zones
6.	Driveway Design

Topic #1: Intersection Sight Distance

The Green Book addresses intersection sight distance (ISD) on p. 774-800. When compared to the Blue Book criteria, the Green Book now presents criteria for left- and right-turning vehicles (Cases IIIB and IIIC) and now bases all ISD criteria on the type of traffic control. These observations on ISB are presented for discussion:

1. *Assumptions of Driver on Major Road.* Cases IIIB and IIIC assumes that the driver on the major road maintains the design speed or that he/she reduces speed to the average running speed. On low-volume highways, a higher assumed speed reduction may be appropriate. On high-volume highways, it may be unsafe to assume any reduction in speed. On multi-lane highways, the driver on the major road may have an opportunity to change lanes.
2. *Trucks.* The criteria for Cases IIIB and IIIC are based on passenger car acceleration rates (1937 data). ISD criteria, assuming a truck as the design turning vehicle, would be considerably higher. There may be a point at which turning truck volumes are high enough to govern.
3. *Minimum Criteria.* It could be argued that, if the driver on the major road has sufficient distance to stop, then the intersection is reasonably safe. This may be especially applicable to low-volume intersections.
4. *Height of Object.* The Green Book assumes 4.25 feet as the object height. However, a stopped driver may not be able to detect an on-coming vehicle when its roof is just barely in view. This would suggest an object height of, perhaps, 3.75 feet may apply.

5. *Location of Eye*. The Green Book establishes a distance of 10 feet between the edge of travel lane and car bumper. However, this does not establish the location of the eye, which would be approximately 5-10 feet behind the bumper. Also, at intersections between low-speed and/or low-volume roads, it maybe reasonable to assume that a vehicle will "creep" closer than 10 feet to the travel lane.

Topic #2: Shoulder Widths

Rural: The Green Book presents specific criteria on shoulder widths on rural highways in Chapters V-VIII. For all classes of highway other than divided highways, these criteria are based solely on traffic volumes. These observations are presented for discussion.

a. Other Factors. The shoulder width criteria could also reflect other factors (e.g., design speed).
b. Rural Arterials. Specifically, the 10-foot shoulder width for rural arterials (DHV>400) may be considered more than is necessary for these facilities. An 8-foot shoulder width might be considered as an alternative on 2-lane rural arterials.

Urban. The Green Book does not present specific, numerical criteria for shoulder widths on urban highways and streets (other than freeways). It does note, however, the benefits of shoulders. Many factors might influence the decision on shoulder widths on urban streets, including:

a. traffic volumes,
b. operating speeds,
c. demand for right turns,
d. multi-lane/two-lane,
e. roadside development, and
f. available right-of-way.

Can a basis be developed upon which the Green Book could present specific criteria for shoulder widths on urban streets?

Topic #3: Design Speed

The Green Book defines design speed as the maximum safe speed that can be maintained over a specified section of highway when conditions are so favorable that the design features of the highway govern. Chapters V-VIII present specific criteria for design speeds on rural highways based on terrain and/or traffic volumes., The criteria for urban highways and streets is presented in a range of volumes. These observations are presented for discussion:

1. *Roadside Development (Rural)*. Many rural highways pass through relatively developed areas. The design speed criteria for these facilities might also reflect the extent of roadside development. This would be especially applicable to rural arterials where the Green Book criteria (p. 534) are based solely on terrain considerations.
2. *Posted/Legal Speed Limit*. The FHWA has taken the position that the design speed should equal or exceed the anticipated posted or legal speed limit. Should the Green Book discuss a recommended relationship between design speed and posted or legal speed?
3. *Average Running Speed*. Figure II - 19 (p. 70) presents the assumed relationship between design speed and low-volume average running speed. This relationship is built into several geometric design elements (e.g., lower SSD value, lengths of acceleration/deceleration lanes). Note that the Green Book uses the design speed for the upper SSD values. The basis for the relationship between design speed and average running speed is described on p 69. Is this a valid relationship? Should the volume-based relationship in the 1985 *Highway Capacity Manual* be used? If so, how should the Green Book be modified?
4. *Existing Highways*. Although the Green Book applies to new construction/reconstruction projects, it nonetheless may also be applied to project on existing highways (e.g., 3R). For these projects it may be warranted in some cases to conduct field studies to determine the existing speeds (e.g., 85th percentile). Should the Green Book discuss a recommended procedure for determining design speed on existing highways.

Topic #4: Application of Stopping Sight Distance

The Green Book could be modified to present refinements in the application of the stopping sight distance (SSD) criteria to vertical and horizontal curves. These observations are presented for discussion:

1. *Height of Eye*. NCHRP 270 "Parameters Affecting Stopping Sight Distance" recommends lowering the height of eye from 3'-6" to 3'-4".
2. *Height of Object*. NCHRP 270 recommends lowering the height of object from 6" to 4" to be compatible with the clearance of today's vehicles. From another perspective, an 18" height of object, which is the approximate height of taillights, may be appropriate as a minimum control.
3. *Grade Correction*. The Green Book (p. 142-143) discusses the grade correction to the SSD formula. At crest vertical curves, the grade correction may apply. Assuming a worst-case scenario (object at

VPT), the braking action would occur on the downgrade portion of the curve. This would increase the braking distance. Should the Green Book address the grade correction on crest vertical curves?

4. *Horizontal Curves*. Although the Green Book applies to new construction/reconstruction projects, it nonetheless may also be applied to projects on existing highways (e.g., 3R). For these projects it may be warranted in some cases to conduct field studies to determine the existing speeds (e.g., 85th percentile). Should the Green Book discuss a recommended procedure for determining design speed on existing highways.

Topic #4: Application of Stopping Sight Distance

The Green Book could be modified to present refinements in the application of the stopping sight distance (SSD) criteria to vertical and horizontal curves. These observations are presented for discussion:

1. *Height of Eye*. NCHRP 210 "*Parameters Affecting Stopping Sight Distance*" recommends lowering the height of eye from 3'-6" to 3'-4".
2. *Height of Object*. NCHRP 270 recommends lowering the height of object from 6" to 4" to be compatible with the clearance of today's vehicles. From another perspective, an 18" height of object, which is the approximate height of taillights, maybe appropriate as a minimum control.
3. *Grade Correction*. The Green Book (p. 142-143) discusses the grade correction to the SSD formula. At crest vertical curves, the grade correction may apply. Assuming a worst-case scenario (object at VPT), the braking action would occur on the downgrade portion of the curve. This would increase the braking distance. Should the Green Book address the grade correction nc rest vertical curves?
4. *Horizontal Curves*. Several observations to the Green Book discussion (p. 243-247) are relevant:

   a. NCHRP 270 presents a formula for determining clearance requirements for SSD for the entering and existing portions of the curve.
   b. The line of sight will be affected by upgrades and downgrades.
   c. The location of eye will be affected by roadway superelevation.
   d. Assuming a 6" object, guardrail at a 27" height or a CMB at 32" may block the line of sight at the second intercept with a barrier.

Topic #5: Roadside Clear Zones

The Green Book on p. 371 references the 1977 AASHTO *Guide for Selecting, Locating and Designing Traffic Barriers* for determining roadside clear zones. This publication is being revised and will be called a *Roadside Design Guide*. The draft of the new Guide has incorporated, in a more explicit manner, the clear zone adjustments for side slopes, traffic volumes and horizontal curvature. The new Guide also presents criteria for 70 mph which, for example, includes a 36' clear zone for a tangent section with flat side slopes. The following observations are presented for discussion:

1. *Context*. Many design practitioners distinguish between "policy" publications (Green Book) and "guide" publications (Barrier Guide), with "policy" carrying the greater weight in application. In this context, should the Green Book elaborate on its unqualified reference to the Barrier Guide for clear zones?
2. *Low-Speed Rural Roads*. For rural collector and local roads with a design speed plus or minus 40 mph, the Green Book designates a minimum clear zone at 10". The Green Book could state whether or not any adjustments should be made for side slopes, curvature, etc. to be consistent with the Barrier Guide approach.
3. *Urban Streets*. Where curbs are present, the Green Book recommends a 1.5' minimum clearance behind curbs. However, curbs will not redirect a vehicle except at low speeds and shallow impact angles. Where a vehicle encroaches beyond a curb, the 1.5' clearance may not be adequate. On the other hand, the options are limited on an urban street and, in some cases, even the 1.5' clearance may be difficult to attain. Should the Green Book present additional guidance for clear zones on curbed urban streets?

Topic #6: Driveway Design

The Green Book only briefly addresses the design and location of driveways. The Green Book could be modified by discussing the following driveway design criteria:

1. location and spacing (e.g., minimum distance to intersecting road or other driveway).
2. 1-way vs. 2-way operations,
3. design vehicle selection,
4. turning radii,
5. minimum and maximum widths,
6. maximum change in grade without a vertical curve at driveway entrances and along the driveway proper,
7. maximum grade on driveway proper, and
8. driveway criteria for intersection sight distance.

The design criteria may be based on driveway type (residential, commercial or industrial) and highway functional class. As an alternative to modifying the Green Book, would it be appropriate to propose that AASHTO prepare a separate publication on driveway design similar to the ITE publication?

WORKSHOP SESSION #3

EVALUATION

OPPORTUNITIES FOR UPDATING AND ENHANCING THE GREEN BOOK

For each issue, please provide an evaluatin from 0 to 10. This will indicate the over-all importance of pursuing the topic in future updates of the green Book. An evaluation of "10" represents the highest rating. An evaluati of "0" reflects an opinion that the issue does not merit further evaluation.

Please check the appropriate box:

- ☐ State Transportaton/Highway Agency
- ☐ Federal Agency
- ☐ Research Consultant
- ☐ Design Consultant
- ☐ Other ____________________

Topic	Title	Overall Importance
1.	Intersection Sight Distance	________
2.	Shoulder Widths	________
3.	Design Speed	________
4.	Application of Stopping Sight Distance	________
5.	Roadside Clear Zones	________
6.	Driveway Design	________
7.	____________________	________
8.	____________________	________
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WORKSHOP SESSION #4

GEOMETRIC DESIGN RESEARCH

Focus

The primary focus of Workshop #4 was to identify research needs in geometric design. The findings from the research, if appropriate, should be incorporated into the Green Book and into a systematic design process. The Workshop also discussed the mechanics of how these findings can be expeditiously incorporated.

Prepared Issues

There are many candidate issues which could have been addressed in this Workshop, and all participants had an opportunity to express their views. However, to provide some framework for discussion, five research topics were identified for initial discussion:

1. intersection sight distance,
2. stopping sight distance,
3. reduced lane/shoulder widths on urban freeways,
4. relationship between geometric design elements and traffic control devices, and
5. relationship between accidents and geometric design.

A brief discussion was prepared on each research topic, and a few relevant observations were made. By no means were those observations considered all inclusive; they were intended to initiate the dialogue. The observations lead to other aspects of the topic which merit discussion. For each issue, the Workshop attendees discussed currently available studies which address the topic and what additional research was needed to help resolve the issue.

Open Discussion

After discussion of the prepared issues, the Workshop was opened to any issues which the participants believed merited discussion. These were related to specific issues (e.g., the two-way, left-turn lanes or warrants for spiral curves) or broader issues (e.g., geometric design consistency).

Implementation

The Workshop attendees also discussed the implementation of research results. In particular, the group discussed the mechanical process of incorporating any important findings into the Green Book.

Evaluation

After a discussion of all issues presented, the Workshop attendees evaluated each issue on a scale of 0 to 10. The objective was to provide a relative indication of the overall value of pursuing research on these topics.

WORKSHOP SESSION #4, Discussion Topics

Topic #	Title
1.	Intersection Sight Distance
2.	Stopping Sight Distance
3.	Reduced Lane/Shoulder Widths on Urban Freeways
4.	Relationship Between Geometric Design Elements and Traffic Control Devices
5.	Relationship Between Accidents and Geometric Design

Topic #1: Intersection Sight Distance

The Green Book addresses intersection sight distance (ISD) on p. 774-800. When compared to the Blue Book criteria, the Green Book now presents criteria for left- and right-turning vehicles (Cases IIIB and IIIC) and now bases all ISD criteria on the type of traffic control. These observations are applicable relative to research on the ISD model are presented for discission:

1. *Acceleration Rates.* For stop-controlled intersections, the assumed acceleration rates for passenger cars are based on studies reported in 1937. Several more recent studies have suggest that drivers today choose to accelerate from a stop at an intersection at a faster rate.
2. *Trucks.* The Green Book ISD criteria for Cases IIIB and IIIC do not consider trucks, which would yield considerably higher distances. However, there may be some threshold at which truck turning volumes are high enough to govern and, therefore, warrant the use of a design truck.
3. *Assumptions of Driver on Major Road.* Cases IIIB and IIIC assume that the driver on the major road maintains the design speed or that he/she reduces speed to the average running speed. On low-volume highways, a higher assumed speed reduction may be appropriate. On high-volume highways, it may be unsafe to assume any reduction in speed. On multi-lane highways, the driver on the major road may have an opportunity to change lanes.

4. *Minimum Criteria*. It could be argued that, if the driver on the major road has sufficient distance to stop, then the intersection is reasonably safe. This may be especially applicable to low-volume intersections.
5. *Height of Object*. The Green Book assumes 4.25 feet as the object height. However, a stopped driver may not be able to detect an on-coming vehicle when its roof is just barely in view. This would suggest an object height of, perhaps, 3.75 feet may be appropriate.
6. *Location of Eye*. The Green Book establishes a distance of 10 feet between the edge of travel lane and car bumper. However, this does not establish the location of the eye, which would be approximately 5-10 feet behind the bumper. Also, on low-speed and/or low-volume roads, it may be reasonable to assume that a vehicle will "Creep" closer than 10 feet to the travel lane.
7. *Driveway Sight Distance*. It may be appropriate to develop separate criteria for sight distance requirements at driveways.
8. *Gap Acceptance*. As an alternative approach to ISD, gap acceptance may be appropriate. It could be argued that drivers are, in effect, determining whether or not a given maneuver is safe.

Topic #2: Stopping Sight Distance

NCHRP 270 *Parameters Affecting Stopping Sight Distance* presents many recommended changes to the exiting SSD model. The more significant recommendations include:

1. using a controlled braking action instead of a hurried, locked-wheel stop;
2. deleting the lower SSD values on the basis that drivers do not slow down on wet pavements;
3. using a 3'-4' height of eye; and
4. using a 4" height of object.

The following observations relative to further research on the SSD model are presented for discussion:

1. *Assumed Vehicular Maneuver*. At higher design speed, it may be inappropriate to assume a driver will elect to stop when confronted with a small object. In fact, most drivers will probably go around the object if possible. Therefore, on high-speed facilities, a lane change may be a more appropriate assumption in the SDD model.
2. *Braking Distances*. The "controlled" braking distances in NCHRP 270 were based on one study. It may be appropriate to examine braking distances indepth. In addition, braking distances on grades may merit further study.
3. *Limits of Driver Vision*. The SSD model assumes the pavement is wet, which suggest poor visibility. Under these conditions, drivers may not be able to see a 6" object at the distances which result from the SSD model, especially at higher speeds.
4. *Height of Object*. NCHRP 270 recommends lowering the height of object from 6" to 4" to be compatible with the clearance of today's vehicles. From another perspective, an 18" height of object, which is the approximate height of taillights, maybe appropriate as a minimum control.
5. *Grade Correction*. The Green Book (P.142-143) discusses the grade correction to the SSD formula. At crest vertical curves, the grade correction may apply. Assuming a worst-case scenario (object at VPT), the braking action would occur on the downgrade portion of the curve. This would increase the braking distances in the SSD model.
6. *Horizontal Curve*. SSD application to horizontal curves may merit further investigation considering:

a. The line of sight will be affected by upgrades and downgrades.
b. The location of eye will be affected by roadway superelevation.
c. Assuming a 6" object, guardrail at 27" or a CMB at 32" may block the line of sight at the second intercept with the barrier.

Topic #3: Reduced Lane/Shoulder Widths on Urban Freeways

As traffic volumes increase on urban freeways, one available option is to increase the number of through lanes by decreasing the lane and/or shoulder widths. This option has received considerable attention in areas of restrictive right-of-way and high construction costs (e.g., on a viaduct). these observations about research on reduced lane/shoulder widths on urban freeways are presented for discussion:

1. *Left Shoulder*. A 10' left shoulder offers an inviting area for increasing the number of through lanes. It may be appropriate to establish how critical the left shoulder is to safety and operations.
2. *Operations Factors*. Narrower lanes may impact traffic operations by, for example, increasing the number of lane encroachments.
3. *Trucks*. The number and size of trucks and their impact on freeways with narrow lanes and shoulders could merit investigation.
4. *Freeway/Ramp Junctions*. The safety and operation of these areas may be impacted by reduced lane/shoulder widths.

5. *Safety*. Additional through lanes may tend to improve safety while narrower lanes and shoulders may tend to decrease safety.
6. *Trade-Offs*. The final analysis would compare the benefits of additional through lanes (improved level of service at relatively low cost) against the operational consequences.

Topic #4: Relationship Between Geometric Design Elements and Traffic Control Devices

The impact of geometric design and traffic control devices are interrelated. Ideally, one will complement the other to create an operationally smooth highway system. However, this may not always be true. The following observations apply to potential research on the relationship between geometric design elements and traffic control devices:

1. *Information Processing*. Both geometric design and traffic control devices are part of the information processing performed by drivers. Their inter-relationship could perhaps merit further study.
2. *Location of Traffic Control Devices*. The compatibility between the physical location of traffic control devices and geometric design elements could perhaps merit further study.
3. *Design Speed vs. Posted Speed*. The posted speed limit creates definite driver expectations which should be reflected in the design speed selection. The relationship between average running speed and posted speed may also merit further study.
4. *Passing Maneuver*. The Green Book criteria for passing sight distance and the MUTCD criteria for marking no-passing zones are based on different operational assumptions. This may lead to confusion, and it may be practical to more closely relate the two.
5. *Yield Signs*. Intersection sight distance may be a relevant factor in the selection of a yield sign for the minor road of an intersection. This could be addressed in the MUTCD.
6. *Interchanges*. Traffic control and geometric design are especially interrelated for highways approaching and passing through interchanges.

Topic #5: Relationship Between Accidents and Geometric Design

Numerous studies have attempted to establish the relationship between geometric design elements and accident probability. Frequently, the results are subject considerable interpretation and often conflict with the results of other studies. These efforts are further frustrated by many other factors. These include inadequate accident data and the difficulties of sorting out the combined effect of several geometric elements on accident causation. Yet, the highway community could realize significant benefits from understanding these cause-and-effect relationships, if a reasonable level of confidence could be associated with the results. Regarding the value of further research, three schools of though may merit discussion:

1. It is, in fact, practical to determine the relationship between accidents and a geometric design element (or combination of elements) with a reasonable level of confidence. Further, this knowledge would have practical value in the application to geometric design on an analytical basis (e.g., in a benefit/cost model or as part of a systematic design process). Therefore, it is warranted to pursue further research to establish and validate the relationship between the two.
2. Research conducted on a selective basis has a reasonable chance of establishing the relationship between geometric design and accident probability. This, in turn, will provide some practical insights into safety and may be useful for more sophisticated applications (e.g., benefit/cost models and a systematic design process). Therefore, it is warranted to select carefully and pursue research studies to establish the relationship between the two.
3. It is unlikely that the highway design community can ever reach a consensus on the relationship between accidents and geometric design. Further, the practical value of the information may be limited. Therefore, it is not warranted to pursue further research to establish the relationship between the two.

WORKSHOP SESSION #4

EVALUATION

GEOMETRIC DESIGN RESEARCH

For each issue, please provide an evaluation from 0 to 10. This will indicate the over-all importance of pursuing research in the topic. An evaluatin of "10" represents the highest rating. An evaluation of "0" reflects an opinion that the issue does not merit further research

Please check the appropriate box:

- ☐ State Transportation/Highway Agency
- ☐ Federal Agency
- ☐ Research Consultant
- ☐ Design Consultant
- ☐ Other ____________________

Topic	Title	Overall Importance
1.	Intersection Sight Distance	______
2.	Stopping Sight Distance	______
3.	Reduced Lane/Shoulder Widths on Urban Freeways	______
4.	Relationship Between Geometric Design Elements and Traffic Control Devices	______
5.	Relationship Between Accidents and Geometric Design	______
6.	____________________	______
7.	____________________	______
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PART 3: CONFERENCE PAPERS

The AASHTO Review of The Green Book

By: Frank D. Holzmann, Chief Engineer,
Highway Design, Texas Department of Transportation

Abstract

The Chair of the American Association of State Highway and Transportation Officials (AASHTO) Subcommittee on Design has appointed the AASHTO Task Force on Geometric Design to address the upgrade of the Green Book. The first task is to prepare a revision of the current edition. This will entail an evaluation of the need, and the necessary revision of related geometric design documents, whether ultimately incorporated into the revised Green Book or developed for separate publication. This paper summarizes the results of the task force review and assessment of the current document on a chapter-by-chapter basis. It includes identification of the need for defining additional design vehicles, coordination with the *Highway Capacity Manual* (HCM) 1985, and a review of the stopping sight distance guidelines. The update process will include review of all applicable research of recent date

The AASHTO Review of the Green Book

The Chair of the AASHTO Subcommittee on Design, Marcus L. Yancey, has appointed the AASHTO Task Force on Geometric Design to address the update of the Green Book.

The objectives and scope of this task force are to provide a focal point and working group for developing and recommending AASHTO geometric design criteria. This assignment includes formulating new and revised criteria to keep current all geometric design standards, policies, and guides.

The first and specific major task of the task force is to prepare an updated revision of *A Policy on Geometric Design of Highways and Streets*, 1984 (the Green Book). This will entail an evaluation of the need and the necessary revision of related geometric design documents whether ultimately incorporated into the revised Green Book or developed for separate publication.

The task force met in Des Moines, Iowa, on October 11 through 15, 1987. The meeting goals were to:

- Review the Green Book from an overall perspective (adequacy, conflicts and improvements);
- Review comments from all the states; and
- Review applicability of recent research generated by the last update.

I will now go through each chapter and discuss some of the areas of the Green Book that the task force felt needed to be addressed.

Foreword

The applicability of the Green Book toward new construction and reconstruction needs to be further clarified. Reference to *Special Report 214: Designing Safer Roads: Practices for Resurfacing, Restoration, and Rehabilitation*, is also needed. Superseded reference documents need to be updated and or removed.

Chapter I: "Highway Functions"

There appear to be no changes of substance that are needed as we see it now.

Chapter II: "Design Controls and Criteria"

- Tables and figures will be updated to include four new vehicles; conforming to the Surface Transportation Assistance Act of 1982 (STAA), truck, double-trailer combination (turnpike double), trip-trailer configuration and a motor home pulling a boat. The format of the tables and turning radii figures will remain the same.
- Acceleration and deceleration charts will be updated based on more current information.
- Speed is an area of concern that has not yet been resolved. Many comments were received suggesting new definitions of design speed, operating speed and running speed. The relationship between design speed and posted speed appears to be causing problems to many people. The use of anything except design speed in the various design tables throughout the book has also been questioned. No consensus appears to be developing in regard to any of this and we may decide to leave it as is.

- The entire section on highway capacity, pedestrians, and various other references to capacity or level of service throughout the chapter is being reviewed and brought into conformance with TRB *Special Report 209: Highway Capacity Manual*, 1985 (HCM).
- Consideration will be given to areas on driver performance to include areas involving effects of aging.
- References to 55 m.p.h. will be removed.

Chapter III: "Elements of Design"

- Stopping sight distance will be reviewed considering recommendations in NCHRP *Report 270: Parameters Affecting Stopping Sight Distance*. I might add that, as a personal viewpoint, I feel there is a great need to take a fresh look at all parameters involved in stopping sight distance.
- There is a need to resolve the passing sight distance conflict between the Green Book and the Manual on Uniform Traffic Control Devices (MUTCD).
- Tables for a maximum superelevation rate of 0.12 will be placed in the Green Book, as they were previously in the Red Book.
- Research on weight/horsepower ratio of trucks will be reviewed to determine if the 300 weight horsepower ratio of trucks is still appropriate. This may affect design of climbing lanes as well as other features which are modified for grades.
- The section of pavement widths will be modified to accommodate the new design vehicle described in Chapter II - a new double, a new triple, and a motor pulling a boat.
- Additional information will be provided on multiple, shorter, climbing lanes, truck pullovers, and passing lanes as described in the Federal Highway Administration (FHWA) publication *Low Cost Operational and Safety Improvements for Two-Lane Roads*.

Chapter IV: "Cross Section Elements"

- There is a need to update charts from the HCM to reflect the current publication.
- The dates of the reference material need to be updated.
- All reference to the Barrier Guide will be updated to reflect the renamed and revised AASHTO Roadside Design Guide. It will reflect the fact that the AASHTO Design Guide is a *guide*, not *policy*. It will also reflect updated changes to the area of drainage channels and side-slopes as well as barriers, all in conformance with the new guide.
- The noise section needs to incorporate the new FHWA Noise Handbook information when it becomes available.
- Curb cuts for handicapped need to be updated to reflect and reference new Uniform Federal Accessibility Standards.

Chapter V: "Local Roads and Streets"

- No Significant changes are planned now.

Chapter VI: "Collector Roads and Streets"

- Most changes will be relatively minor. They involve changing and updating references to other publications as well as wording to indicate "guide" or "reference" rather than "shall use" terminology.
- The revision of stopping and or passing sight distances will be needed when they become available.
- Other revisions will be necessary when Chapter VI is compared to any changes in Chapters II, III, IV, V, & VII.

Chapter VII: "Rural and Urban Arterials"

- The usable shoulder width, for highways with volumes of 400 and over DHV, needs to be revised from 10 to 8 feet.
- Design speed for rural arterials, needs to be revised to indicate 40 m.p.h. as being an appropriate design speed when conditions dictate.
- The sections on medians need to be redrafted to consider operational problems with wider medians on divided highways with at grade intersections.
- References to other guides and policies need to be revised by deleting the "shall use" wording.

Chapter VIII: "Freeways"

The only significant revision currently planned is to correct an error on page 631, and elsewhere as necessary, which specified 12 feet paved shoulders are preferred on freeways when the truck traffic exceeds 250 DHV. This was a carry-over from the Red Book and it should have read "250 DDHV" to recognize the one-way intent. There are numerous insignificant revisions such as correcting typographical errors in the original prints, clarifying certain language and eliminating redundant or unnecessary ROW dimensions.

Chapter IX: "At-Grade Intersections"

The major issues to be addressed involve:
- Incorporating of the performance characteristics of larger trucks;
- Including the HCM 1985 information;
- Reviewing the lengths of deceleration lanes used at turning lanes at intersections;
- Reviewing the methods of determining sight distance requirements for turning vehicles at intersections;
- Reorganizing information within the chapter so it will flow more smoothly; and
- Insuring that the most current vehicular performance characteristics are incorporated, such as acceleration and deceleration rates.

Chapter X: "Grade Separations and Interchanges"

- There is a need to address many editorial changes.
- This chapter also needs to be coordinated with the HCM.
- Discussions of X-pattern ramps will be added;
- Pavement widths need to be reviewed for the new design vehicle.
- Tables, text, and sketches for ramp entrances need to be coordinated.
- Text and sketches regarding major forks as well as branch connections need to be clarified.

Status of Research

Research has been performed in various areas of applicability for the Green Book. It will probably be addressed in more detail later in the program. Specific research to be reviewed by the task force for this Green Book update is as follows:

- Elements used to establish sight distance values,
- Weight/Horsepower ratio,
- Side friction factors for superelevation,
- Shoulder contrast,
- Cross-over crown, and
- Acceleration and deceleration lengths for terminals.

Summary

These are some of the items which the AASHTO Task Force feels need to be addressed in the update of the Green Book.

Review of the 1984 AASHTO Policy (Green Book) - A Consultant's Perspective

By: Joel P. Leisch, President,
Jack E. Leisch & Associates

Abstract

The paper outlines briefly the highway engineering consultant's functions, clients, and philosophy in accomplishing highway geometric design and translates these into requirements for a national geometric design policy. The discussion relates specifically to the 1984 American Association of State Highway and Transportation Officials (AASHTO) publication *A Policy on Geometric Design of Highways and Streets* (the Green Book). General and specific enhancements of the Green Book are suggested consistent with consultant needs and philosophy.

Introduction

Consultants provide a large portion of highway design services to government agencies as well as to the private sector. A geometric design policy should respond to the needs and requirements that the consultant has so that they may provide the best possible service to the client.

This paper briefly outlines the consultants functions, clients, and philosophy in accomplishing geometric design, and translates these into policy requirements. Also, general and specific enhancements of the policy are suggested consistent with consultant needs and philosophy.

Consultant Functions, Clients, and Philosophy

Consultants provide design services beginning with highway planning and ending in construction supervision. The geometric design process in reality begins with highway planning. Too often this task or function is relegated to those who are not familiar with nor have experience in geometric design. It is at this phase of the highway development process that an understanding of geometric design would assure the practicality of implementation.

The next step in the process is functional design. This task is as it sounds, creating a facility that would function physically and operationally and can be constructed. The geometric design (incorporating mathematics into the geometry) precedes preparation of the construction plans. This phase is critical in that it finalizes the geometrics in three dimensions. It should not change the character or intent of the previous phases and does form the bases for the construction plans.

The construction plan phase is primarily detailing the design elements sufficiently for the contractor to construct the facility. Geometric design often becomes a task in this phase associated with the development of sequence of construction and traffic control plans. Once construction begins in the field, occasionally there are design revisions which become necessary. Sometimes these relate to geometrics which need adjustment or change.

Important also is the function the consultant plays in research. The FHWA, National Cooperative Highway Research Program (NCHRP), and state agencies often contract with consultants for research and development type projects. Some of these are related to geometric design and often result in a change or embellishment in the geometric design policy.

The above functions or tasks performed by consultants are accomplished for a variety of clients. These include:

- FHWA;
- State departments of transportation, or transportation or highway departments;
- Counties;
- Municipalities;
- Private developers; and
- Attorneys (litigation, expert witness).

Each has somewhat different needs and it is necessary for the consultant to respond to these while being sensitive to the requirements of a geometric design policy.

A consultant should have a positive and beneficial philosophy in performing the geometric design services for the client. The philosophical approach to geometric design stated below is this consultant's and not necessarily that of all consultants:

- Prepare a design that is in the public good;
- Be creative in the application of design principles, criteria, and standards;
- Work cooperatively with the client;
- Desire to develop a good concept and execute it well in design; and
- Comply with standards and criteria.

Consultants Requirements in a Geometric Design Policy

A geometric design policy must respond to the requirements of the unique role of the consultant in providing various clients with an array of design services. It must also reflect the consultants' philosophy toward his clients and his functions. Listed below are some of the geometric design policy requirements for consultants.

- Basic criteria and standards presented for all roadway types.
- Firm guidelines but flexibility in application.
- Description of procedures in assembling design elements in producing design the engineering method.
- Description of a systems engineering approach to the highway planning and design process.
- Examples of design situations where decisions related to trade-offs must be made.
- Responsive to defense in litigation.
- Adequate references.

General Attributes and Enhancements-1984 Policy

There were several changes and improvements made in the 1984 Green Book in relation to the previous policies. There are two things which make the new policy better than previous ones. The first of these is the presentation of criteria by functional classification. This is an asset in finding and identifying criteria. The second relates to modifications in criteria based on research and operational experience.

Generally, however, there are some enhancements or improvements which are needed to satisfy the requirements of the consultant. These may include the following:

- Less rigid phraseology related to criteria and standards;
- More responsive to litigation;
- More criteria for urban projects for all functional classes;
- Better guidelines on how to compromise when it is not possible to comply with criteria;
- Need the description of systems engineering approach to geometric design to reflect capacity, operations, environmental, and other requirements;
- A description of procedures to accomplish geometric design-plan, profile and cross section;
- Closer marriage between operations and capacity, and geometric design;
- Emphasis on design consistency related to operations; and
- More comprehensive references.

Specific Enhancements to Policy

Within the above general enhancements there are, of course, some specific improvements that are needed. Others at the conference have identified several of these. Presented here, are several which specifically relate to the author's experience and concern.

Sight Distance Influenced by Barrier and Parapet

With improvements being made to freeways and expressways, the engineer is often confronted with the problem of inadequate stopping sight distance on curves due to the installation of a concrete barrier. Sometimes this occurs when lanes are added in the median of a freeway or expressway and the resultant median has narrow shoulders. It also occurs on curved ramps on structure where the parapet may not be offset sufficiently from the travelled way.

The question is how to deal with these situations recognizing right-of-way constraints and implementation costs. Figures 1, 2, and 3 portray examples of possible solutions to this problem. However, these are not the only solutions. It is felt that a geometric design policy needs to provide guidance in dealing with sight distance problems and the trade-offs in design.

Design Consistency Methodology

There has been much discussion and research related to harmonizing traffic operations and geometrics. Because it is the geometrics of a roadway which influence its performance (operations and accidents), it is necessary to incorporate analysis procedures which produce a design which reflects safe and efficient traffic operations. A concept was developed several years ago based on a design principle and available data which could form the basis for one of these analysis procedures. Figures 4 and 5 describe the design principle and its application through a speed profile technique to produce an operationally consistent design.

Collector Distributor Roads

During the 1960's, 1970's, and early 1980's, several freeways and interchanges have been improved by the addition of collector distributor (C-D) roads. While the 1984 Green Book addressed these in Chapter VIII, it needs expansion and definition based on recent and past experience. Some criteria, based on experience, not in the 1984 Green Book are presented in Figure 6.

Design Compromise

On many new location and major reconstruction projects compromise in design criteria may be required if a project is to become viable. This may relate to horizontal, vertical or cross-sectional geometry. The designer needs guidance in determining those features which can be compromised and the trade-offs involved. The following lists considerations involved when contemplating such a compromise:

- Functional classification,
- Operational requirements of drivers and vehicles,
- Interrelationships between vehicles, and
- Sensitivity to variable conditions.

Study and Design Process-Systems Engineering Approach

All previous policies in one form or another described a procedure for highway planning and design. The 1984 policy has no procedure described. A procedure is needed to provide guidance for all geometric designers so all aspects and considerations of the design process can be understood and implemented to assure a design that is sensitive to all requirements. An example of a procedure is presented in Figure 7.

Summary and Recommendations

The items presented here are expressly for enhancing the understanding of the design community in relation to the consultants role and philosophy in accomplishing geometric design and the associated requirements in a design policy. It is hoped that the specific enhancements and improvements discussed will provide some guidance for future policy revisions.

It is recommended that a comprehensive survey of users of the 1984 Green Book be conducted and AASHTO, Transportation Research Board, American Society of Civil Engineers (ASCE), Institute of Transportation Engineers (ITE), American Road and Transportation Builders Association (ARTBA), and so forth, work together in formulating future revisions.

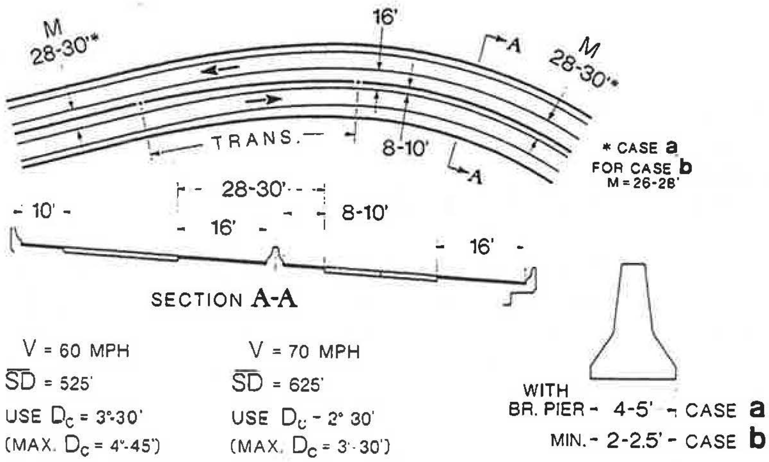


FIGURE 1 Freeway sight distance with median barrier.

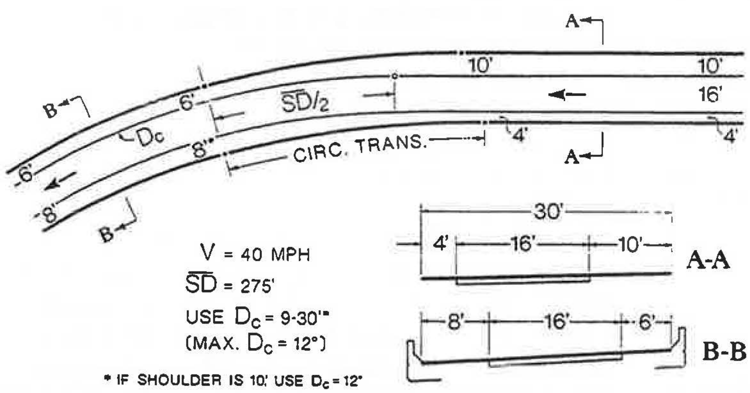


FIGURE 2 Provision for sight distance on ramp with barrier - curve left.

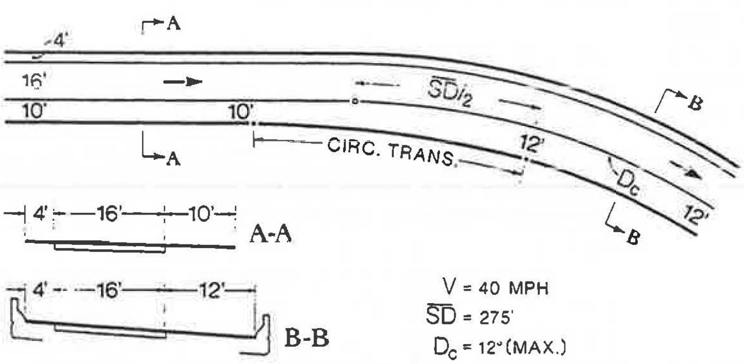
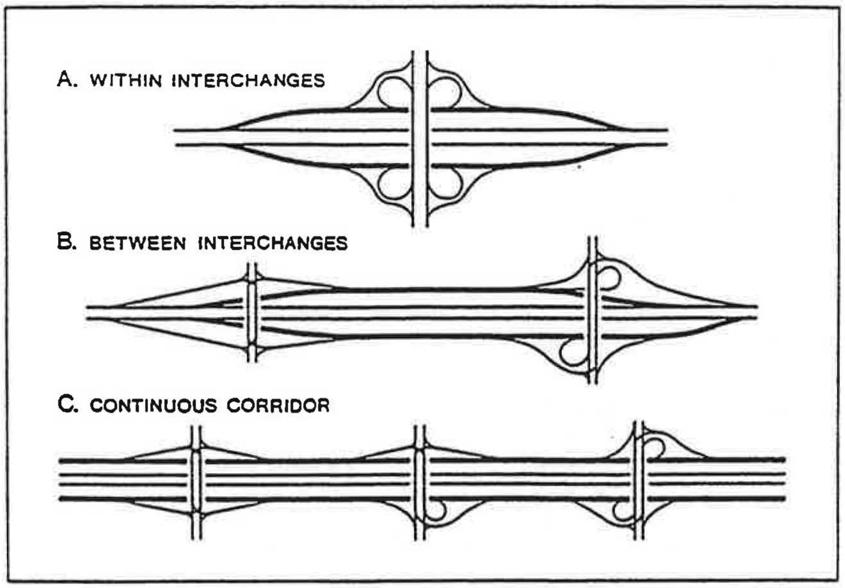


FIGURE 3 Provision for sight distance on ramp with barrier - curve right.



APPLICATION OF C-D ROADS

BASIC LANE CONFIGURATIONS				ADT DESIGN CAPACITY
C-D ROAD	CORE	CORE	C-D ROAD	
2	3	3	2	120 - 160,000
3	3	3	3	150 - 200,000
3	4	4	3	180 - 250,000

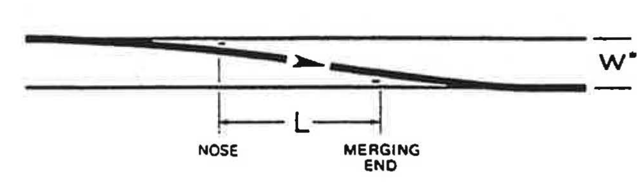
LANE CONFIGURATIONS FOR C-D ROAD SYSTEMS

ROADWAY	DESIGN SPEED			
	USUAL		MINIMUM	
	MPH	KPH	MPH	KPH
CORE*	70	110	60	95
C-D ROADS*	60	95	50	80
TRANSFER ROADS	65ᶠ	100	55ᶠ	90

* Maximum differential in design speed between Core Roadways and C-D Roads is 10mph (15kph)

ᶠ Also applies to each transfer road within basket weave.

DESIGN SPEED SELECTION



	NOSE TO MERGING END DIMENSION		
	MINIMUM	PREFERRED MIN.	DESIRABLE
L	200' (60m)	400' (120m)	600' (180m)
W*	35' (10m)	70' (21m)	110' (33m)

* Internal dimension between roadways.

TRANSFER ROAD DESIGN REQUIREMENTS

FIGURE 4 Collector-distributor roads - criteria (metric equivalents rounded for design purposes).

DESIGN PRINCIPLE

THE 10 MPH *(15 KPH)* RULE

- WITHIN A GIVEN DESIGN SPEED, POTENTIAL AVERAGE PASSENGER CAR SPEEDS GENERALLY SHOULD NOT VARY MORE THAN 10 MPH *(15 KPH)*
- A REDUCTION IN DESIGN SPEED WHERE CALLED FOR NORMALLY SHOULD NOT BE MORE THAN 10 MPH *(15 KPH)*
- POTENTIAL AVERAGE TRUCK SPEEDS GENERALLY SHOULD BE NOT MORE THAN 10 MPH *(15 KPH)* BELOW AVERAGE PASSENGER CAR SPEEDS AT ANY TIME ON COMMON LANES

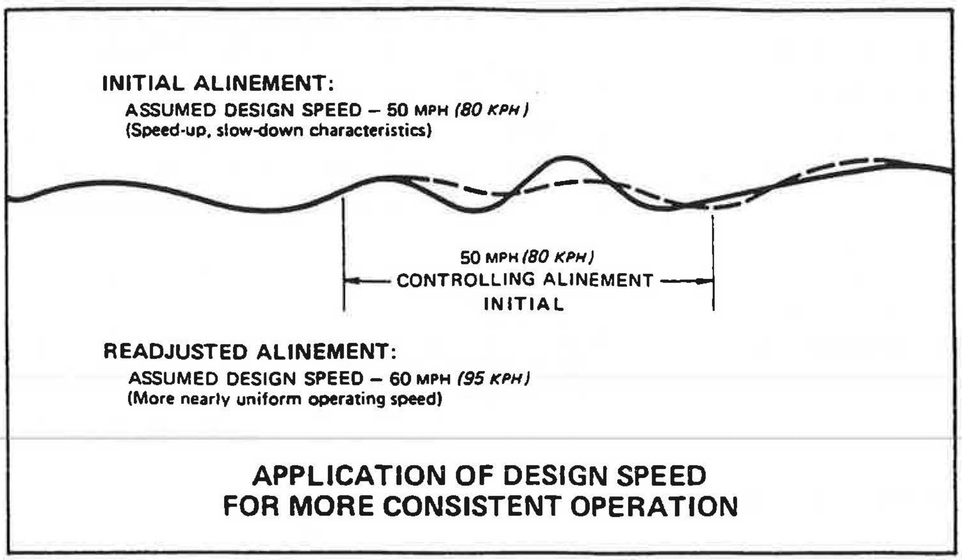


FIGURE 5 Operational consistency through geometric design.

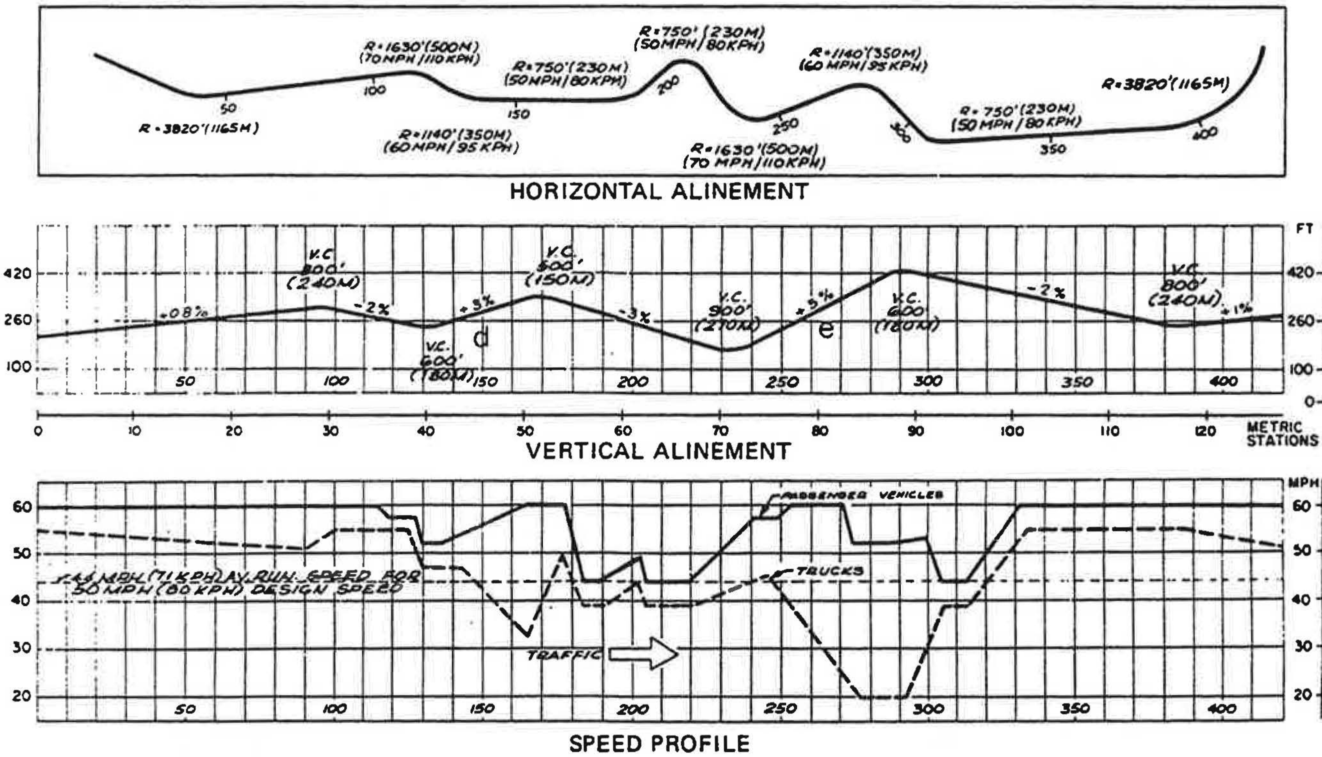


FIGURE 6 Operational consistency through geometric design, example of speed profile.

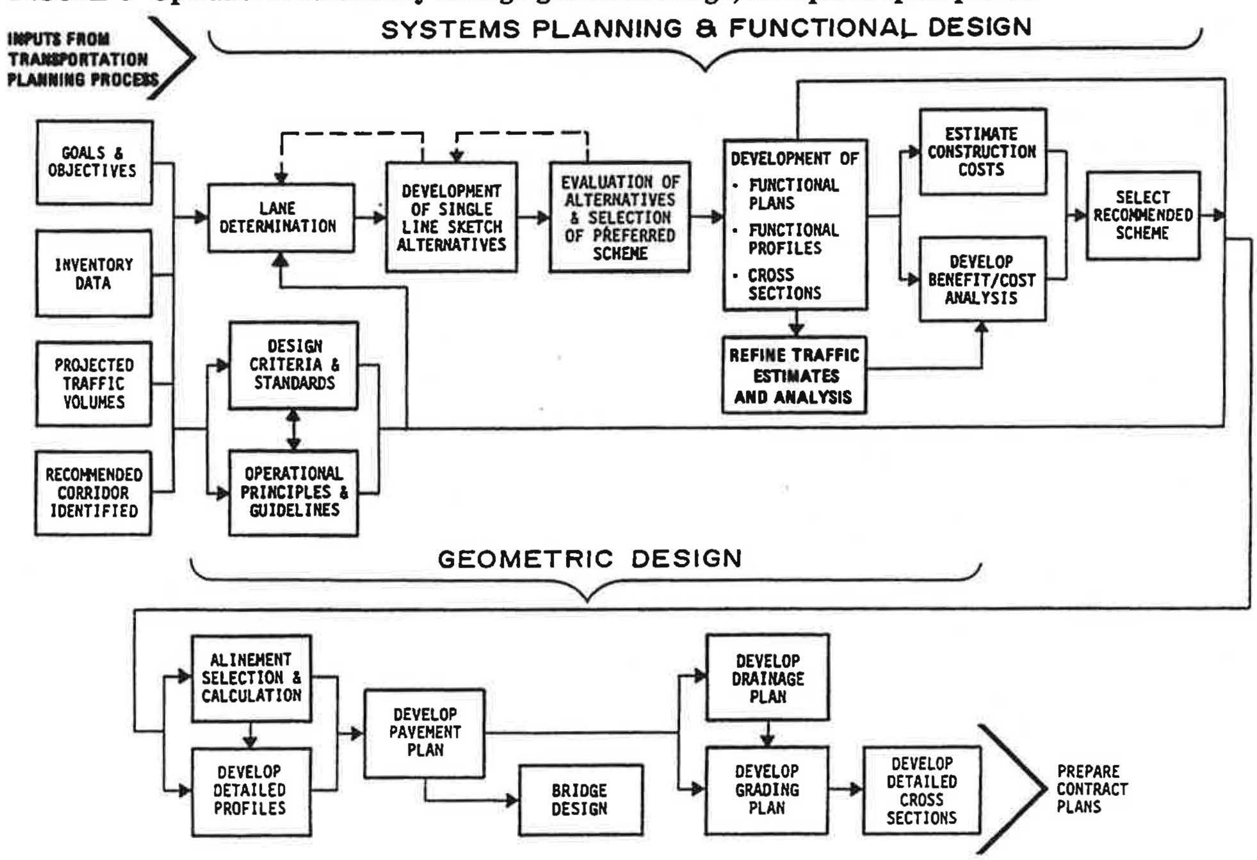


FIGURE 7 Planning/design - an integrated procedure.

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Reflecting Operational Effects of Geometrics Throughout the Design Process

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Abstract

This paper reviews methods to assure that operational effects of geometrics are reflected throughout the highway design process. A more systematic design process may be the key to assuring that operational effects of geometrics are thoroughly considered. A description and flow diagram of a systematic design process is presented and the elements used to reflect operational effects of geometrics in design are critiqued. Several specific needs that must be met to make the design process more systematic are described.

A critical part of the geometric design process is assuring that the operational effects of geometrics are adequately reflected in the highway design. Great attention to detail is needed to assure that the final design of the highway provides the desired levels of service and safety to highway users. The central theme of this paper is the development of a systematic highway design process that focuses on the interrelationships between design elements, rather than treating each element separately, it has the potential to improve the operational and safety effectiveness of highway designs.

The paper is organized in three major sections. First, an overview of the highway design process is presented, showing the structure of a more systematic design process. Next, the paper identifies the elements used in geometric design to reflect operational effects. These elements are the key to achieving highway designs that meet the needs of the driver. Finally, the paper discusses some steps that must be taken to achieve a more systematic design process and thus increase the likelihood that the geometric designs for our highways will meet the needs of drivers.

Highway Design Process

Geometric design involves establishing the physical dimensions of the highway so it can operate efficiently and safely. Thus, geometric design is an optimuazation process and not just an attempt to satisfy the requirements of a set of design policies or standards.

Figure 1 presents a flow diagram of a systematic highway design process structured in a manner to assure that the operational effects of geometrics are considered. As shown in the figure, the highway design process consists of four major stages:

1. Establish a set of objective design goals,
2. Define design constraints and their relationship to highway design parameters,
3. Develop a comprehensive design policy, and
4. Prepare the geometric design for individual projects.

However, systematic design requires a process that is broader than just the four steps listed above. This broader structure for the design process was first suggested by Glennon and Harwood in a 1978 paper entitled, *Highway Design Consistency and Systematic Design Related to Highway Safety* (1). That paper describes the systematic design process far more comprehensively than will be attempted here, although a few key points about the structure of the process will be made.

The first step of the systematic design process is to establish a set of goals for the highway design process, including aspects such as:

1. Safety,
2. Efficiency,
3. Economy,
4. Comfort,
5. Maintainability, and
6. Environmental quality.

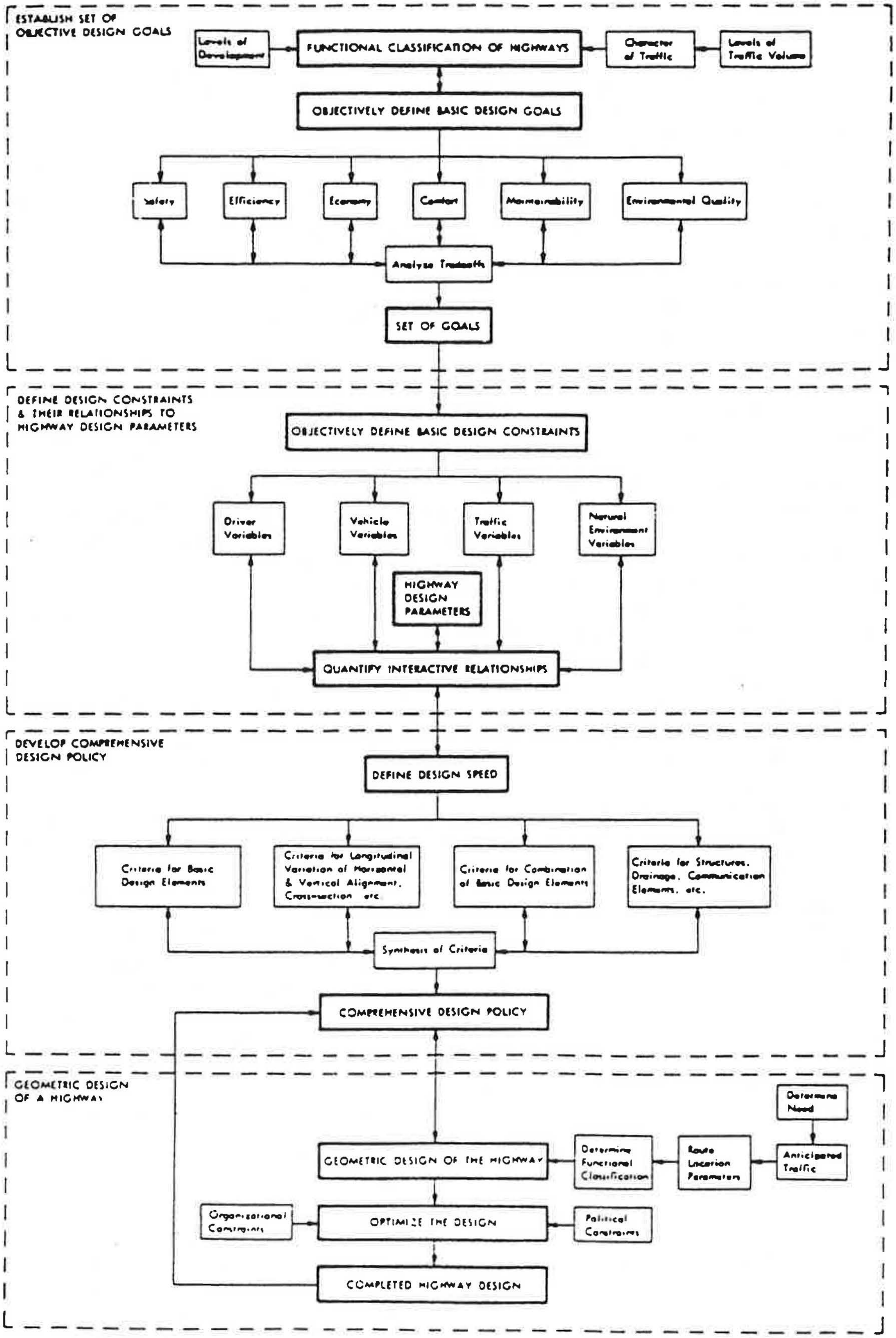

FIGURE 1 The highway design process.

The goals need to be objectively defined and quantified within the framework set by the functional classification of highways. Thus, for each functional class the design process should explicitly identify what levels of these goals we expect to achieve and how trade-offs between these goals are to be addressed. Current and past geometric design policies have never attempted to define goals in this fashion.

The second stage of the design process is to develop an objective definition of the basic constraints and interactive relationships that control the highway design process, including driver, vehicle, traffic, and environmental constraints and their interactive relationships. The systematic design process should identify how these constraints set the requirements for the development of design criteria. In particular, a comprehensive understanding of driver capabilities and limitations and how they constrain the design process is critical.

Next, the systematic design process must be based on a complete understanding of the relationships between design goals, design constraints, design elements, and appropriate measures of effectiveness, including measures of traffic operations and safety. Establishing these interactive relationships requires research into the fundamental operational and safety effects of geometrics and the availability of those research results in a form where they can be directly employed by designers.

The research results must be used to develop a comprehensive design policy that addresses basic design elements such as horizontal and vertical alinement and cross-section and combinations of those elements.

Finally, when all of this has been accomplished, the comprehensive design policy can be used in the geometric design of individual projects. The steps in the design of individual projects include:

1. Highway planning,
2. Functional design,
3. Geometric design and preliminary engineering,
4. Construction plan preparation, and
5. Construction management.

Of these stages, the greatest emphasis on the consideration of operational effects must be in the functional design and geometric design and preliminary engineering steps.

The next section of the paper describes the elements used in geometric design process to reflect operational effects. These elements are the key to producing a design that meets the needs of the driver.

Elements Used in Geometric Design to Reflect Operational Effects

The elements used in geometric design to reflect operational effects include:

1. Functional classification,
2. Design speed,
3. Design vehicles, and
4. Highway capacity analysis.

Each of these elements will be discussed briefly.

Functional classification systems are used to describe highways for their role in the highway network, such as principle arterial, minor arterial, major collector, minor collector, and local. The 1984 Green Book does a much better job than its predecessors in defining geometric design policies for functional classifications and this must be considered one of the major advances in highway design in recent years.

Highway design is probably more sensitive to speed than any other factor, not only because the ability to stop and corner is a function of the square of speed, but also because the impact forces of a collision are a function of the square of speed. Most designers would agree that design speed is a key element in reflecting operational effects and particularly safety effects in geometric design.

The 1984 Green Book defines design speed as "The maximum safe speed that can be maintained over a specified section of highway when conditions are so favorable that the design features of the highway govern."

This definition is abstract and does not lend itself to serving as an objective basis for design. Under conditions so favorable that factors other than the design features of the road do not influence speed, it is difficult to imagine any feature other than horizontal curvature that controls maximum safe speed. If this is the case, the design speed of a highway can never be made consistent because it is infinite on tangents and restricted on curves.

Another example of inconsistency in the application of design speed is evident in the selection of superelevation rates for horizontal curves. Two completely identical curves would have different design speeds if they are located in states that use different maximum superelevation rates. For example, a 3 degree curve with a superelevation rate of 0.06, would have a design speed of 50 m.p.h. if located in a state with a maximum superelevation rate of 0.10, but would have a 70 m.p.h. design speed if located in a state with a maximum superelevation rate of 0.06. Given this anomaly, it is difficult to accept the notion that the current method for determining design parameters for horizontal curves bears a direct relationship to safety.

A more objective method is needed to reflect speed and safety considerations in the geometric design process. One method for accomplishing this may be the use of formal methods of evaluating geometric design consistency. Several methods of this type are in current use, including those of Messer, et al. (3), Leisch (4), and a method developed in Germany (5). These methods for evaluating geometric design consistency are reviewed in detail in the resource materials of Workshop Session 1 presented elsewhere in this volume.

The 1984 Green Book incorporates a range of 10 design vehicles to reflect the role of vehicle characteristics in highway design. These design vehicles include a passenger car, various trucks, buses, and recreational vehicles. However, the primary role of these design vehicles in the policy is to provide for consideration of vehicle off-tracking in intersection and horizontal curve design. Most other design elements are based on the passenger car and do not consider other vehicle types, such as the truck that may be more critical.

Finally, operational effects of geometrics are considered through highway capacity and level of service analysis to assure that the highway is designed to serve the traffic demands expected to be placed on it. The Highway Capacity Manual (HCM) 1985 (6) provides several analysis procedures that have distinct advances over those of previous editions including, the procedures for two-lane highways and intersections with signals.

To this point, the paper has dealt with the geometric design process as it currently exists. The next section of the paper addresses possible changes that should be considered to achieve a more systematic design process.

Achieving a More Systematic Design Process

The achievement of a more systematic highway design process will largely be a function of our ability to perform and disseminate the results of better research on the operational effects of geometrics. In a systematic design process, design criteria must be defined objectively on the basis of valid research on their operational effects. This requires three essential activities. First, research funding and administrative procedures must be in place to see that the needed research is performed. Second, research results require comprehensive evaluation and review to assure that they are valid. Third, valid research findings must be incorporated in design policies and made known to designers.

To achieve these goals, the following needs should be met:

- Better feedback is needed about current operational and safety problems, so this information can be put back into the design process. We need better methods of documenting operational experience and communicating that experience to future designers.
- More research is needed on the operation and safety effects of geometric design elements.
- A formal mechanism is needed for review and assessment of highway research results for incorporation in design policies. If specific research results are found to be valid, they should be reflected in design policies. If available research results on specific issues are found to be invalid, the need for further research on that issue should be feed back into research funding decisions.
- Valid research results should be synthesized in documents intended for use by designers and policymakers. An excellent example of this type of research synthesis is the TRB *Special Report 214: Designing Safer Roads—Practices for Resurfacing, Restoration and Rehabilitation* (7). However, there should be an ongoing activity to update research syntheses of this type and keep them current.
- Better analytical tools are needed to allow designers to determine the traffic service and traffic safety implications of their decisions. More microcomputer software and broader analytical capabilities in CADD systems are especially important in this respect.
- More flexibility is needed to base design on cost-effectiveness rather than fixed standards. Microcomputer-based economic analysis tools could be especially valuable in assuring that the limited funds available for geometric improvements are spent effectively.

Conclusions

The achievement of a more systematic design process can be an important step in improving the extent to which highway designs reflect the operational effects of geometrics. The current highway design process is often interpreted as requiring fixed standards that may be cost-effective in some but not all cases. A systematic design process could assist designers in obtaining the maximum operational and safety benefits from the funds available for highway improvements, but the achievement of this goal will require a better understanding of the relationships between geometric elements and their operational and safety effects.

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Driver Behavior Approach to Highway Design

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Abstract

The paper provides an overview of a human factors approach to understanding the relation between geometric design and observed traffic behavior. The model focuses on the sources of information inherent in the geometry of the roadway that allows the drivers to locate themselves in time and space. Immediate information coupled with previous experience allow drivers to use selectively the geometry to maintain speed and position control. This kind of model permits a direct analysis of the geometric characteristics of the highway for driver response and hence, traffic behavior. The model is applied to specific elements, including lane width, grade, ramps and stopping sight distance. In each case the analysis leads to different results from those in the Green Book, it also provides a different perspective on the process of establishing design standards.

Introduction

The basis for highway design has largely been on empirical studies of traffic behavior. Such approaches have led to aggregate models of traffic, from which specific design criteria have been derived. In general, this class of macroscopic models leads to design derived from basic vehicle performance characteristics coupled to field observations of traffic behavior. More recently this view of traffic has been expanded with a variety of operations research methods that allow a more precise mathematical and statistical definition of traffic behavior and a fundamental means of manipulating traffic and design variables, for example, simulation.

Another approach to traffic and highway design is microscopic in nature and is based upon the analysis of driver behavior. The philosophical rationale for such an approach is straightforward. The highway system functions because the driver can link the characteristics of the vehicle to the geometric characteristics of the highway. The driver is the guidance and control mechanism of the system and the basic determinant of its efficiency and safety. In general this approach to design has not been extensively used by the highway designer except in regard to some basic anthropometric considerations, such as sign and signal heights, and sight distance.

Over the past half century there has been an extensive amount of research in human controlled systems. This has led to the design of systems far more complex than highways that humans could guide and control very efficiently. Although considerable human factors research has been done in highway transportation, little control theory has found its way into geometric design. However, with the knowledge base now available, it is increasingly clear that many of the issues in highway design can better be resolved using a human factors approach than the conventional aggregate and mechanistic models most common in the field.

The objective of this paper is summarize a human factors model in driving and to identify some of its applications to highway design. To do this, it is necessary to provide a framework for the application of the approach.

The Driving System

At its heart the highway system requires each driver to locate continuously his or her vehicle relative to the geometric properties of the highway and relative to other vehicles in the immediate environment. To accomplish this, the driver must detect, abstract, and define the critical information in the highway and traffic environment essential for speed and position control. Since this information may be discrete, such as an intersection, sign, and signal, or continuous, for example, velocity, pavement, and pavement markings, the driver must be able to select the information critical for control. In either case the driver must be able to relate that information in both time and space as the basis for projecting future position and speed. It is out of this analytic or cognitive process that a driver can make decisions concerning control changes and they're ordering in time and space.

This dynamic information processing activity determine the specific control responses that will be imposed on the vehicle. Essentially, the driver has only two control dimensions in driving, for example, speed and position. However, these may be relative or absolute. It is absolute in the sense of lateral positioning relative to the highway or the perceived speed at which a given geometry may be tracked. It is relative in the case of speed when following another vehicle.

The results of this process generate changes in the information received by the driver. A control response changes environmental information and these changes are measures of control effectiveness. Such feedback allows the driver to exercise continuously fine control over the system. Indeed without it, the highway system would hardly junction at all.

Ideally, we have a closed loop control process, the mathematics for which have been well worked out. One of the interesting aspects of the highway system is that in a variety of situations, the loop is not completely closed, for example, the time delays in information acquisition are excessive or the feedback is discontinuous. Such factors account for a significant amount of the variability observed in most empirical studies of traffic. It occurs simply because of system design.

There is one final consideration in understanding the basis of driver behavior. This is that humans learn and can employ past experience to reduce their own response variability and to compensate for ambiguities in system performance and design. This precognitive behavior generally includes not only past experience, but also interpretation of information which the driver will not use immediately. The driver can thus plan and order future control requirements. This capacity allows drivers to compensate for static and dynamic ambiguities which are characteristic of highway operations. It is worth noting that in most modern human-machine system design this class of precognitive behavior is minimized which generally produces markedly reduce variability in system performance.

The Information System

In this paper the focus will be on the information acquisition task of drivers. This focus is taken because it is the structure of the driving environment that is the basic element of guidance and is primarily determined by highway design. The fundamental question is: What are the sources of information available to the driver that are essential to overall vehicular guidance and control? There are at least five such environmental sources whose information characteristics determine driving performance:

1. *Roadway geometrics*. The design of a highway is the basic source of information for drivers. Its properties, the standard ones of grade, curvature, and lane width, are the determinants for drivers as to when in time, where in space and the magnitude of control response they will have to initiate.

2. *Traffic dynamics*. Driving almost always involves interaction among vehicles. In this context each driver must not only abstract information from the roadway geometry, but also obtain relative information, such as the relative speeds and positions of vehicles in the traffic stream. The ability to obtain and maintain these metrics are essential to understanding traffic flow and the interrelation between traffic and geometrics.

3. *Traffic control*. Traffic engineering has developed a wide range of techniques for providing information to drivers. These may be categorized as static or dynamic control. The latter are those that provide drivers with continuous information about the state of the roadway. Pavement markings and delineators are two examples. Static control are point sources of information defining discrete conditions in the highway and traffic environment. Signs and signals are examples.

4. *Vehicle dynamics*. The driver also receives information from the dynamic properties of the vehicle. some sources are discrete, for example, speed, but the important ones are continuous. At one extreme these are proprioceptive cues such as the pressure on accelerator or brake pedal. At the other are kinesthetic cures derived from vehicle response characteristics as well as control inputs. Thus in curve tracking, centrifugal forces are perceived by the drivers through vestibular response and through whole body kinesthetics. All of these provide direct and feedback information to drivers that modulate control behavior.

5. *The driving system*. All the sources of information defined above are the template for guidance and control. In the dynamics of driving, the human must select, order, and integrate these information sources in order to effectively operate the system. The quantity, quality, and dimensions of the information provided in time and space determine system efficiency and safety. it is also important to recognize that although the human capacity to detect and discriminate information in all the dimensions discussed is extremely fine, there are three limitations to this capacity:

a. The rate at which information may be processed is limited. Even with coding this rate rarely exceeds 6 bits per second.

b. The human processes sensory information sequentially and thus must switch between sources of information. This requires time sharing among sensory modes.

c. Although very sensitive in the sensory modes used in driving, information processing is easily degraded by the properties of the information source, noise and the environment in which information is presented.

If the key information sources and the ways they are used by drivers are identified, it becomes possible to identify the characteristics of geometric design, traffic and their interactions that will produce effective driving performance. Conversely, utilizing a human information processing model it becomes possible to establish design criteria that will insure effective performance.

Information Processing and the Driving Environment

From the previous discussion it becomes appropriate to identify the major dimensions of information needed by drivers to effectively operate the system. It also is possible to define the key elements of highway design which are the source of that information. In essence, the elements of design provide the basis for examining what information the driver uses to guide the vehicle. Table 1 lists major elements of geometric design with their objective metrics. Also shown are the equivalent subjective metrics. The latter represent the basic dimensions by which drivers locate themselves relative to the characteristics of the visual environment.

TABLE 1 OBJECTIVE AND SUBJECTIVE METRICS FOR SELECTED GEOMETRIC ELEMENTS

Geometric Element	Objective Measure	Subjective Measure
Grade	FT/FT	PHI-Vert Ang.Vel
Curve	Radius-FT/Deg	W-Horiz. Ang. Vel
Lane Width	Feet	Theta-Vis. Angle
Taper	FT/FT	W-Horiz. Ang. Vel

To understand the relation between the design dimensions and their subjective counterparts, a model of human response is necessary. First, in driving the human is receiving information in time as well as space. That is, drivers may be viewed as fixed in space with the environment moving toward them. The spatial characteristics are thus seen for all practical considerations as a vector; time and space are seen simultaneously.

Second, all points in space are seen as relative to the eye. That is, the space-time continuum is defined by the human in trigonometric terms. At the limit of zero velocity, real or apparent, the roadway or elements within in it are seen in terms of visual angles relative to the eye. At any real or apparent velocity, the roadway or elements within it are seen in terms of angular velocity.

Finally, the size of the field of view which the driver uses is limited in both length and width. Drivers cannot use all the information within their field of view. Rather the field is restricted to that cone essential for effective vehicle control. As will be discussed, the radius and altitude of this cone is a function of speed. In sum, it is suggested that drivers employ a dynamic visual field which becomes the fundamental source of information for vehicular control.

The basic information used for control is a cone, extending laterally and vertically with a solid angle of 2-3 degrees. The altitude of the cone is determined by speed. All elements lying within the cone are seen as fixed points. All those lying outside of the cone are seen as moving relative to the eye. Therefore, as a driver looks ahead, elements within the field are seen as fixed points or areas. The visual angles that such elements subtend at the eye are a function of distance. Indeed, the primary basis for distance judgement is the transformation of visual angle. This is a statement of the law of the visual angle. The relationship with distance is shown in Figure 1. It is important to note that as objective distance increases the visual angle decreases but non-linearly. At relatively long distances the relation with visual angle is proportional to distance and linear. However, at such small angles the driver's accuracy in estimating distance decreases markedly. Judgements are further reduced because of head and body movement in a moving vehicle. This is one reason why a distinction has been made between static and dynamic acuity. Practically, this simply means that objective distances normally provided with signing have little meaning or utility to drivers.

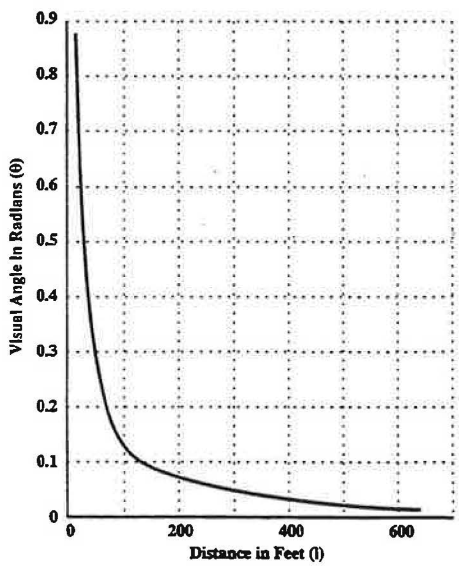


FIGURE 1.

No matter what happens in distance judgement, drivers exercise control in speed and position. In the simplest case, a driver in free flow on a tangent section must maintain position in the lane. How does a driver know whether he or she is following the lane or drifting from it? In this case, the driver is engaged in a simple compensatory tracking task: the driver responds to deviations in the heading angle of the vehicle. The basic paradigm is shown in Figure 2 If a driver views the road ahead and is centered in the lane with the path of travel parallel to the center and edge lines, the visual angle subtended by the pavement edge line with the line of regard and the that subtended by the center line are equal. However, the tow lines are moving relative to the driver at a velocity related to vehicle speed. The visual angle subtended by the lane markings must also be changing. The equation for visual angle may now be differentiated to define the angular velocity of pavement markings at a distance, "l", from the driver's eye. This function is:

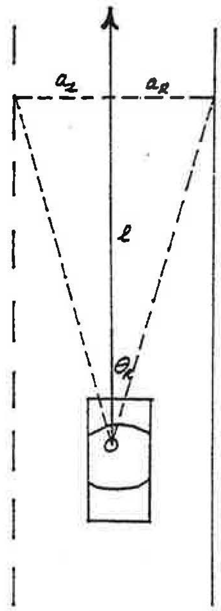


FIGURE 2 Paradigm of lane following.

1. $wh\ (av)\ /\ (a^2 + l^2)$

Where:

wh = horizontal angular velocity in rads/s
v = speed in f/s
a = lateral distance in feet
l = forward distance in feet

As may be noted, angular velocity, "w", decreases rapidly with increasing distance ahead. The function is shown in Figure 3. The human has a lower limit below which motion is undetectable. This is the threshold of angular velocity. Although threshold values vary considerably, sufficient evidence exists to suggest that in the driving system the driver threshold is approximately 0.004 rads/sec. Regardless of the value, as the driver views the road ahead while travelling at some speed, V, there is a distance, 1, where the edge and center line, or their equivalent demarking the lane, will have a component of angular velocity just at the driver's threshold. This cone may be defined as the driver's action field, that is, the distance at which elements entering the visual field generate active response from the driver. Everything outside this field will not be acted upon directly although it may be used precognitively as a means of planning and ordering future actions.

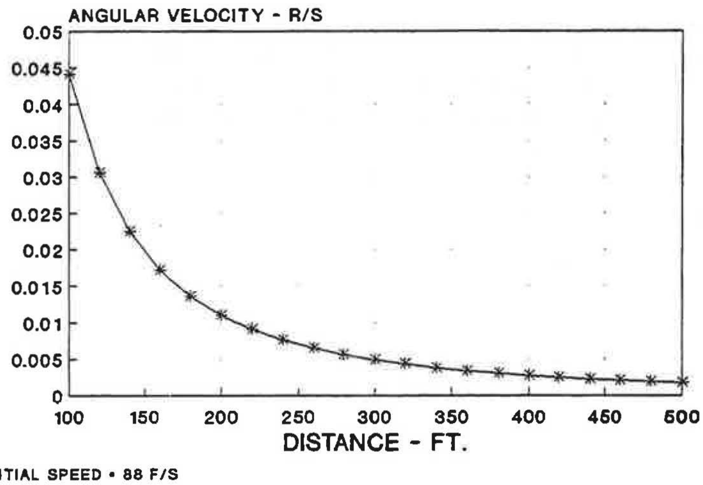


FIGURE 3 Angular velocity.

This basic model can be used to understand how driver's maintain their position in the travel lane. Assume, as in Figure 4, that the driver's heading angle changes such that the vehicle turns toward the right pavement edge. It can be shown that operating at the limits of the action field, where the angular velocity is at threshold, the right lane edge will cease to have a component of lateral motion. Conversely, the other lane edge will have a component of angular velocity well above threshold. This is a direct basis for the driver to initiate a corrective steering maneuver such that the two lines are both returned to threshold. Using angular velocity threshold as a criterion for control, the driver maximizes the time available for control response and has a stable criterion for the type and magnitude of response required. This type of process describes a classical compensatory tracking task. Finally, if the driver responds to a 10 percent change in angular velocity at a speed of 80 f/s, the variance in lane position will not exceed 0.5 to 1.0 foot.

Two conclusions with design relevance follow from this view of driving control on tangents. Firstly, the greater the contrast of the lane edge, the more precisely the driver can locate and maintain the locus of the angular velocity threshold. Thus, high contrast pavement edge lines should lead to lower variability in vehicle placement in the lane.

Secondly, there is an optimum speed for a given lane width. At any given speed, the forward reference distance is that at which the angular velocity of the lane edge is at threshold. Conversely, for any given lane width, the driver will adjust speed such that the lane edge will be at threshold for that visual reference distance. This leads to the conclusion that the narrower the lane width, the lower the speed of travel which is well recognized empirically. We can estimate the nominal speed for any given lane width from equation 1. This is shown in Table 2 and applies to tangent sections only.

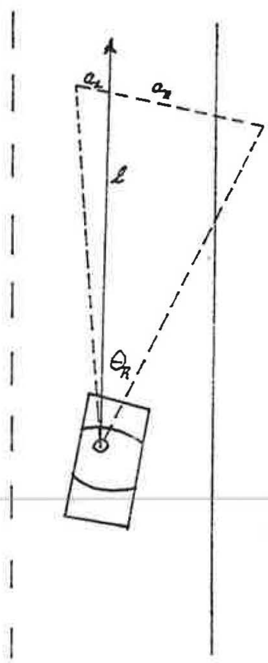


FIGURE 4 Deviation of heading angle.

Sight Distance

The model also provides a means for establishing criteria for sight distance. In the simplest case, a driver proceeding along a tangent section approaches some curvature, horizontal or vertical. If that curvature is great enough, the driver's view of the roadway will become restricted. There is then no feedback information, cognitive or precognitive. The system is operating at least partially open loop. Obviously, one criterion for magnitude of grade is that it never should be great enough to obstruct the driver's view at or closer than the visual reference distance which is defined by the design speed.

Another classic problem can be approached in the same manner: stopping sight distance. The design field has historically confused a static situation with what is, in fact, a dynamic one for the driver. The concern has been with detection distance and vehicle deceleration capability. We would submit that this is not the appropriate starting point. Rather, the question is: At what distance can a driver detect overtaking of an object in the travel lane? Assume first a fixed object located in the center of the lane of travel. The first question is how do drivers know they are closing on that object? If the object is visible, that is, it has spatial extent and contrast, it will have no component of angular velocity for distances greater than the visual reference distance for any object equal or less in size than the lane width. The driver can detect overtaking only discretely, that is, by changes in visual angle from time t^1 to time t^2. The driver cannot detect overtaking. All that drivers can know is that there is a speed difference between their vehicle and the object. It will be only when the object generates a detectable angular velocity that the driver detects closure rate. This distance may be defined as:

2. l = sqrt(a*v' /w)

Where, "a" is the size of the object, "v'" is the relative velocities, and "w" is the angular velocity threshold. If the object is not moving then "v'" is the speed of travel. In this case, the size of the object, "a", determines the distance at which that object generates a threshold angular velocity.

It is hypothesized that a driver approaching a stationary object in the roadway will respond with a braking or steering change when the object generates a detectable angular velocity. Using equation 2, it is possible to calculate the distance at which an object of any size will generate a supra-threshold angular velocity for a given travel speed. This is shown in Table 3. The smaller the object, the closer it must be to the driver before it reaches angular velocity threshold. Given the data in Table 4 it is possible to estimate the mean deceleration required of a driver to come to a stop before striking the object. This is shown in Table 4. Two things should be noted from Table 4. Firstly, the smaller the size of the object to which a driver must respond with braking the greater the deceleration required. Secondly, the deceleration increases inversely, but non-linearly with object size.

If the maximum comfortable deceleration is approximately 12 f/s/s, closure rate must be detected at a distance that will require decelerations less than this criterion value. From Tables 3 and 4 it is possible to estimate minimum stopping sight distance. This is shown in Table 5 for the five object distances and four travel speeds. For values of object size falling above that diagonal, the deceleration required will be less than 12 f/s/s. It is important to note that object size and design speed determine stopping sight distance. There is no way to establish stopping sight distance without specifying both. However, if object size used for a criterion is below about 7 feet there will be no acceptable stopping sight distance for any design speeds greater than 80 f/s or 55 m.p.h.

Finally, it has been assumed that drivers will always decelerate in the face of all objects in their path. Small objects, less than 4 feet in width, do not reach threshold angular velocity at freeway speeds until they are very close to the driver. At these distances it is very unlikely that drivers will use braking as their response. Rather they are more likely to use steering as the collision avoidance control response.

TABLE 2 PREDICTED SPEED AT DIFFERENT LANE WIDTHS

Lane Width-FT	Expected Speed-F/S
9	36
10	50
11	70
12	82
13	91
14	98

TABLE 3 CLOSURE RATE DETECTION DISTANCE

	Object Size-FT				
Approach Velocity-F/S	O.33	1	4	7	9
50	64.2	111.8	223.6	295.8	335.4
70	76.0	132.3	264.6	350.0	396.9
90	86.2	150.0	300.0	396.9	450.0
110	95.3	165.8	331.7	438.7	497.5

TABLE 4 MEAN DECELERATION REQUIRED TO STOP (FT/S/S)

Approach Velocity-F/S	Object Size-FT 0.33	1	4	7	9
50	19.5	11.2	5.6	4.2	3.7
70	32.2	18.5	9.3	7.0	6.2
90	47.0	27.0	18.5	10.2	9.0
110	63.5	36.5	18.2	18.8	12.2

TABLE 5 SAFE STOPPING SIGHT DISTANCE

Approach Velocity-F/S	Object Size-FT 0.33	1	4	7	9
50	none	111.8			
70	none	none	182.3		
90	none	none	none	396.9	
110	none	none	none	none	497.5

Lane Adds and Drops

This same class of analysis can be applied to another classic geometric issue: lane adds and drops. Normally, such lane changes are advertised to approaching drivers using signing. Although a driver has considerable freedom as to when he or she engages in the weave maneuver, the basic criterion for a lane change will be derived from the transition zone, that is, the geometry of the segment preceding the add or drop.

It is the lane drop that is the most problematic for a driver. There are two cases that may be evaluated from a human factors perspective. One is where the driver must respond to the geometry alone. In theory, a lane can simply end. However, all such lane drops involve a taper with American Association of State Highway and Transportation Officials (AASHTO) using a criterion of 50 to 70:1. But why design a taper section? As a driver approaches a lane end, the terminus will be easily detectable. However, the driver will not respond to that locus until it enters the action field. If the terminus is simply the lane end and the driver is travelling at 80 f/s, the angular velocity increases very rapidly, doubling in 100 feet. This will force a driver to respond rapidly either by braking to reduce angular velocity or to initiate a steering maneuver. The first is undesirable for a driver since it increases the relative velocity with respect to the gap acceptable gap. The second requires considerable distance to complete. Indeed, at 80 f/s the order of 200 to 250 feet are necessary which is almost the total distance available to the driver from the point at which the change in angular velocity is detected. In essence, a simple lane drop places a driver in a position of near overload.

If the lane drop design includes a taper section, the information provided the driver is quite different. As the driver approaches the terminus, the right edge of the pavement is perceptually moving closer to the path of travel. In a tangent section, the right lane edge is just at the threshold of angular velocity for the visual reference distance at the speed of travel on the tangent. In the taper, the angular velocity of the lane edge decreases as the driver approaches. As pointed out earlier, the natural response of the driver is to introduce a compensatory steering response to cause the angular velocity to return to threshold. Thus, the taper smoothly leads to a lane change maneuver and does so without inducing a major speed change. Knowing the taper angle, it is possible to calculate the change in position of the vehicle required to drive the lane edge back to angular velocity threshold. Conversely, using this model, the relation between taper angle and yaw velocity may be determined. This should be the criterion for acceptable taper angle. Obviously, it will vary with speed as well as lane width.

The same analysis can be made for speed change lanes. However, from a driver behavior standpoint, the acceleration lane case appears different from the deceleration lane case. In the former, one does not want to force a driver to steer left into the traffic stream. Such a steering maneuver should not be dependent, on geometry, but rather on the driver's decision rule relating to gap acceptability. Hence, in the acceleration lane case, a parallel design is preferable.

In the deceleration case, the opposite operates. A taper expanding to join the ramp provides a direct cure for the driver to diverge. The lane expands to the driver's right so that the angular velocity of the road edge increases as a function of the taper angle. For the diverging driver, a simple compensatory steering control change to reduce that angular velocity to threshold will lead the drivers directly onto the SCL in line with the ramp and will do so with a yaw velocity proportional to the degree of taper. If the exit ramp is a diamond type diverging at a fixed angle, then a taper SCL provides a smooth transition in angular velocity from freeway to ramp.

Generalization of Geometric Design From Driver Behavior

This discussion has focussed on a small set of examples of how geometric design standards can be derived from the key element in system operation: The driver. It is perfectly feasible to expand the general analysis to most central issues in geometric design and highway capacity. The particular focus of this paper is, however, only one of several dimensions that must be included to provide a general model for defining geometric design of highways. For example, this discussion has not spoken to horizontal curvature and the problem of pursuit tracking such curvature requires of the driver. Similarly, there has been no discussion of precognitive behavior which is concerned with the organization and utilization of information available from the geometrics beyond the so-called action field. Drivers are not dumb controllers, nor do they focus constantly at the forward reference distance. Except in extremely complex driving situations, drivers have significant amounts of time to scan the driving environment in all three dimensions with the forward reference distance being a sort of center of gravity of visual focus. Hence, they can project ahead for changes in speed or position that may be required at some time in advance of actual control changes. This process allows for patterning of behavior and thus allowing smooth transitions.

Nor has this discussion considered the differences between familiar versus unfamiliar drivers. It is obvious that drivers learn the geometry they use regularly. Each segment of roadway has its own plan. Drivers learn that plan and can predict the changes. Similarly, the larger environment has fixed elements, such as buildings, flora, texture, and so forth whose location divers learn. This cognitive map provides a base for tracking the environment which is ultimately internalized and used automatically. Since such a learning process is highly individualized, it may be expected to lead to the large variability in observed driver behavior.

All of these higher order guidance and control processes have been developed theoretically in cognitive psychology. Such theory is applicable to both design and operation of the highway system. Combining these with the basic perceptual and analysis processes discussed in this paper it is becoming clear that a comprehensive model of driver behavior is feasible.

Whenever there is a grade, a component of vertical angular velocity will be added to the horizontal. Then at the forward reference distance, the perceived angular velocity will be the vector sum of the two. That is:

3. $$w_t = (w_h^2 + kw_v^2)^{1/2}$$

The visual system is not as sensitive to vertical angular velocity as it is to horizontal, hence the constant "k" in the equation. Its value is approximately 0.9. If the gradient is great enough, the vector sum at the forward reference distance will generate an angular velocity above threshold. For the driver this means that his or her speed is too high for the visual reference distance. This will lead a driver to reduce speed and thus cause angular velocity to return to threshold at that distance.

It is predicted, that there will be a speed reduction approaching a grade of any magnitude. It can be shown that for a driver approaching grade at a speed "v", andhence a forward reference distance "l", the vertical angular velocity can be defined:

4. $$w_v = (k^*r^*v) / l^2$$

Where "r" is the grade in feet and "k" is the coefficient of sensitivity, 0.90. Using equation 3 to determine the vector sum, it is possible to compute the predicted speed reduction for a grade of any magnitude. This is shown in Figure 5 for the case where the initial velocity approaching a grade is 80 f/s. As may be seen, the relation is approximately linear and should be measurable for grades much greater than 2-4 percent. It is interesting to note that we can define a geometric design standard starting from driver behavior that historically has been derived from vehicle characteristics and engineering judgement.

It is also becoming clear that it is no longer necessary to treat the driver as a terra incognita. This has been the history of highway design: largely neglecting the analytic properties of driver behavior and making design decision on the basis of aggregate statistics and or engineering intuition. Accepting the broad base of understanding of the human guidance and control process can provide a more rational and detailed analytic basis for geometric design. Doing so would provide a firmer basis for establishing design criteria as well as a means of predicting the consequences of design decision in specific situations. It also provides a means of predicting the consequences of changes in highway design, vehicle parameters or new control technology.

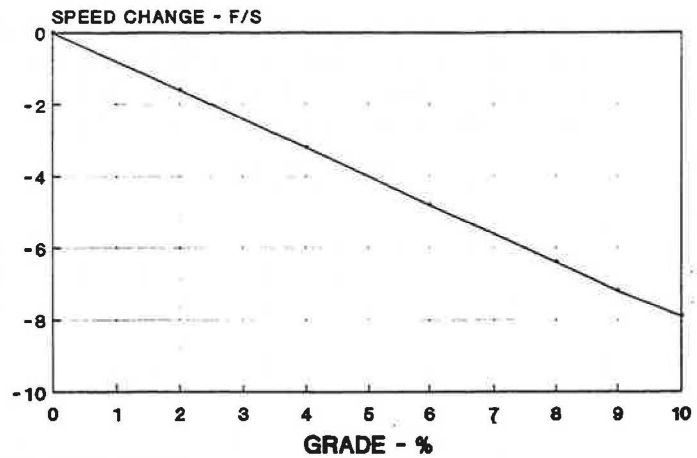


FIGURE 5 Speed reduction due to grade.

Simulation Models of Vehicle Dynamics

By: Brian G. McHenry, McHenry Consultants, Inc., Cary, North Carolina

Abstract

Evaluations of geometric design features of highways and roadsides, with respect to the dynamic behavior of vehicles traversing them, have been supplemented since the late 60's by the use of computer simulation models of vehicle dynamics. This paper discusses the rationale for the use of computer simulation techniques and presents descriptions of two public-domain computer simulation models of vehicle dynamics (HVOSM and UMTRI-PHASE 4). Sample results of several applications of the two programs are included which demonstrate representative interactions between vehicle characteristics and roadway and roadside geometric design features.

Introduction

Evaluation of the geometric design features of highways and roadsides, with respect to the dynamic behavior of vehicles traversing them, has been supplemented since the late 60's by the use of computer simulation models of vehicle dynamics. Rapid advances in the field of micro-electronics in the last decade have made the computerized manipulation of complex equations defining vehicle dynamics over a wide range of operating conditions very feasible, productive and cost effective.

The purpose of this presentation is to review the rationale for the use of computer simulation models of vehicle dynamics in the evaluation and refinement of geometric design features. Also, two public domain computer simulation models of vehicle dynamics will be described and sample applications discussed.

Rationale

The selection of specific full scale experiments to evaluate highway geometric design features is made difficult by the wide ranges of variables that exist in the vehicle population and in operating conditions (e.g., vehicle sizes and characteristics, driver/environmental factors, speeds and maneuvers). Problems associated with the performance and repeatability of full-scale tests, including the selection and/or construction of specific geometric design features to test, instrumentation and the calibration of test instruments and the high unit cost per test run, all detract from a purely experimental approach involving a large number of full scale tests from which to make specific design decisions.

At the other extreme, the use of point-mass equations and/or simplified empirically derived equations to evaluate geometric design features is of questionable reliability. The present vehicle population includes passenger and commercial vehicles with wide ranges of size, weight, drive type, weight distribution, acceleration capabilities and handling characteristics. This diverse vehicle population includes an equally diverse array of drivers varying in experience, capabilities and characteristics. All of the cited variables in the vehicle and driver population need to be considered in an evaluation of geometric design features.

This large gap that exists between the cited extremes of techniques available to evaluate geometric design features, combined with the emerging capabilities and availability of computers in the sixties and seventies provided a logical alternative approach for supplementing our understanding and evaluation of geometric design features.

The basic approach in the utilization of a simulation model of vehicle dynamics is to create a computer code based on fundamental laws of physics, combined with empirical relationships for tires and structural properties, which can be applied so that the responses can be compared with instrumented full scale tests. Once the model is objectively "validated" the researcher can use the model to interpolate and extrapolate test data and test sensitivities to changes in the vehicle, driver and roadway design at a fraction of the cost of the full scale tests. Depending on the degree of sophistication of the simulation model and the simplifying assumptions used to create it, the variables which can be investigated are essentially unlimited. However, as a word of caution, when using simulation models to test the sensitivities of responses to changes in design elements, one must exercise appropriate care in the interpretation of results and in the formulation of conclusions. Limitations inherent in any computer simulation model due to simplifying assumptions and applications outside the range of validation must be properly considered to insure that the results are representative of real world responses and not produced by some inherent artifact of the simulation model. Computer based simulation models should be viewed as one tool of many which can be used to supplement the other "tools" (e.g., full scale tests, sound engineering practices and principles and common sense) to ultimately evaluate a design problem.

Two public domain computer simulation models of vehicle dynamics which have been extensively validated and utilized in addressing geometric design problems are the *Highway Vehicle Object Simulation Model (HVOSM)* (Ref 1&2) and the Truck and Tractor-Trailer Dynamic Response Simulation-Phase4 computer model (Ref 3&4).

Highway Vehicle Object Simulation Model (HVOSM)

In the mid-60's the Calspan Corporation (then Cornell Aeronautical Laboratory, Inc.) began development of a general mathematical model and computer simulation of the dynamic responses of automobiles under Contract CPR-11-3988 with the Bureau of Public Roads. The mathematical model, which was subsequently named the HVOSM, includes the general three-dimensional motions resulting from vehicle control inputs, traversals of terrain irregularities and collisions with certain types of roadside obstacles. The development of the HVOSM included an extensive validation effort within which a series of repeated full-scale tests with instrumented vehicles was performed to permit an objective assessment of the degree of validity of the computer model.

The HVOSM mathematical model consists of up to 15 degrees of freedom; 6 for the sprung-mass, and up to 9 for the unsprung-masses. The mathematical model is based on fundamental laws of physics (i.e., Newtonian dynamics of rigid bodies) combined with empirical relationships derived from experimental test data (i.e., tire and suspension characteristics, load deflection properties of the vehicle structure). The balance of forces occurring within and applied to components of the system are defined in the form of a set of differential equations which constitute the mathematical model of the system

In 1976, after 10 years of development, refinement and applications of the HVOSM by Calspan as well as other research organizations, a Federal Highway Administration (FHWA) contract (DOT-FH-11-8265, Ref.2) was performed by Calspan to document all the various developments, refinements and validations of the HVOSM. Within that contract, two program versions were assembled, the HVOSM version (Roadside Design) and the HVOSM-VD2 version (Vehicle Dynamics).

Since 1976 a number of further refinements and enhancements of the HVOSM-RD2 version have been developed and incorporated by McHenry Consultants, Incorporated,(MCI) under subcontracts with Jack Leisch and Associates (DOT-FH-11-9575, Ref.5), Midwest Research Institute (DTFH-61-80-C-OO146, Ref.6)" Calspan (DTFH61-83-C-00060, Ref.7) and the Highway Safety Research Center of the University of North Carolina (DTFH61-84-C-00067, Ref.8) under FHWA sponsorship as well as through internal research.

Truck and Tractor-Trailer Dynamic Response Simulation-Phase4

Since 1971, the Transportation Research Institute (formerly the Highway Safety Research Institute) of the University of Michigan (UMTRI) has been conducting research under the sponsorship of the MVMA and the FHWA to develop a means of predicting and evaluating the directional response characteristics of trucks, tractor-semi trailers, tractor-trailers and triples. In 1980, UMTRI released the PHASE4 program which constitutes a compilation and consolidation of nearly a decade of development of the existing models into a single program (Ref.3). The PHASE4 program is a time-domain mathematical simulation in which the vehicles are represented by differential equations derived from Newtonian mechanics combined with empirical and/or tabular relationships for some components (e.g., tires) that are solved for successive time increments by digital integration. The mathematical model incorporates up to 71 degrees of freedom with the number of degrees of freedom being dependent on the vehicle configuration and options chosen. The PHASE4 program includes small angle assumptions in its basic mathematical equations which means that in many of the equations, an angle in radians is used in place of the sine or tangent of the angle. As a result, the program is limited to ranges wherein the accuracy of the approximations is acceptable (i.e., angles < 15 degrees).

Sample Applications

In the late 70's and early 80's an FHWA study was conducted by Jack Leisch and Associates (JEL) on Safety and Operational Considerations for the design of Rural Highway Curves (Ref.5) which included the use of the HVOSM and the PHASE4 program to supplement operational field studies of curve sites.

The HVOSM was used to simulate the driver/vehicle operations on a wide range of highway curves. The basic input requirements for the performance of an HVOSM or any simulation run include definition of the vehicle, the roadway and of the driver control inputs.

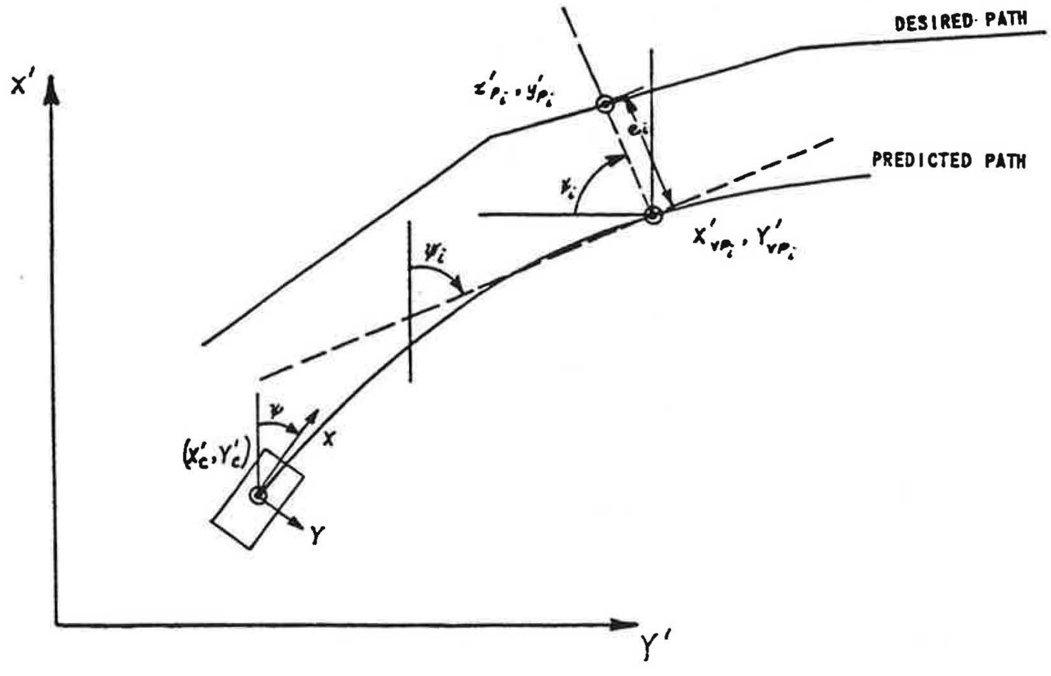
The specification of the vehicle inputs for the HVOSM requires selection of a vehicle type and the creation of corresponding inputs to define the vehicle properties. A growing number of measured vehicle data sets exists which can he supplemented by approximation techniques (Ref. 2).

The specification of the roadway for the HVOSM consists of creating terrain tables to define the elevation of the terrain for each grid segment of the table. HVOSM has the capability of accommodating 5 terrain tables with up to 441 terrain elevation points in each table. An auxiliary Terrain Table Generating program was created as part of the JEL Study to permit the automatic generation of tables for any type of roadway based on standard roadway and shoulder geometric descriptions.

A driver model was also incorporated into the revised HVOSM-RD2 program as a part of the JEL study. It was based on the form of driver model contained in the HVOSM-VD2 model. The revised driver model consists of a polynomial definition of the desired path and a wagon-tongue steer control with a "neuro-muscular" filter to permit variations in the driver observation and response characteristics (Fig.1). The "wagon tongue" form of steer control consists of the use of a line which extends forward of the vehicle centerline at a user specified distance at which an error from the "desired" path is calculated and used as input to the "neuro-muscular" filter. The filter serves to delay the response for a specified perception reaction time after which it applies a correction to the steer angle based on an input gain factor.

Problems which can arise from using a simulated driver control occur when either (1) only optimum driver control is achieved (no dynamic overshoot) and the corresponding justification for the simulation is questionable, or (2) excessively oscillatory steering responses occur which reflect artifacts of the driver model rather than the real world roadway characteristics. Care must be taken to insure that neither of these situations occur and form the basis for an incorrect conclusion.

The basic methodology utilized for the JEL study was to initially compare simulations of optimum driver/vehicle performance on a number of sample curves with calculated lateral acceleration and tire friction factors (i.e., simulating a path-following with a



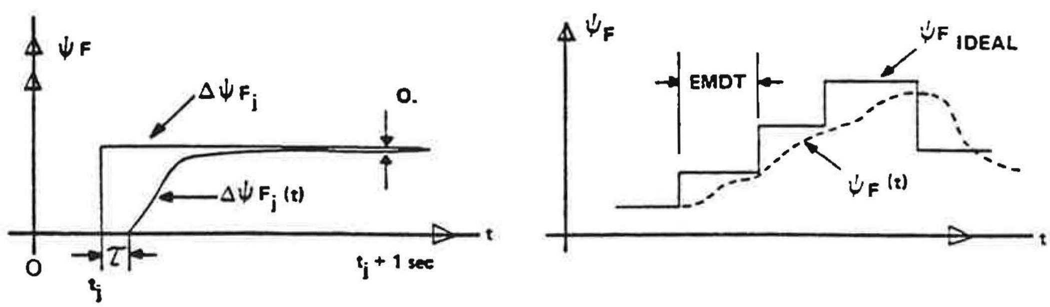


FIGURE 1 HVOSM driver model (from Ref. 2).

minimum of dynamic overshoot of the desired path). Next the driver model of the HVOSM was calibrated to be more representative of the "typical" driver observed in field studies (i.e., a somewhat less than optimum driver who overshoots the desired path radius). Then this "driver" was used to guide the simulated vehicle through a wide range of curve entry runs to test several design variables (i.e., superelevation runoff and runout, spirals, etc.).

The resulting driver model inputs that were selected for the study produced response characteristics representative of the field observations, however, there were some discrepancies later found in the manner in which the critical radius was generated. The drivers observed in the field tended to approach from the outer edge of the curve and follow a spiral path which began approximately 50-100' before the PC and which headed the vehicle to the inside of the curve (Fig.2&3). The

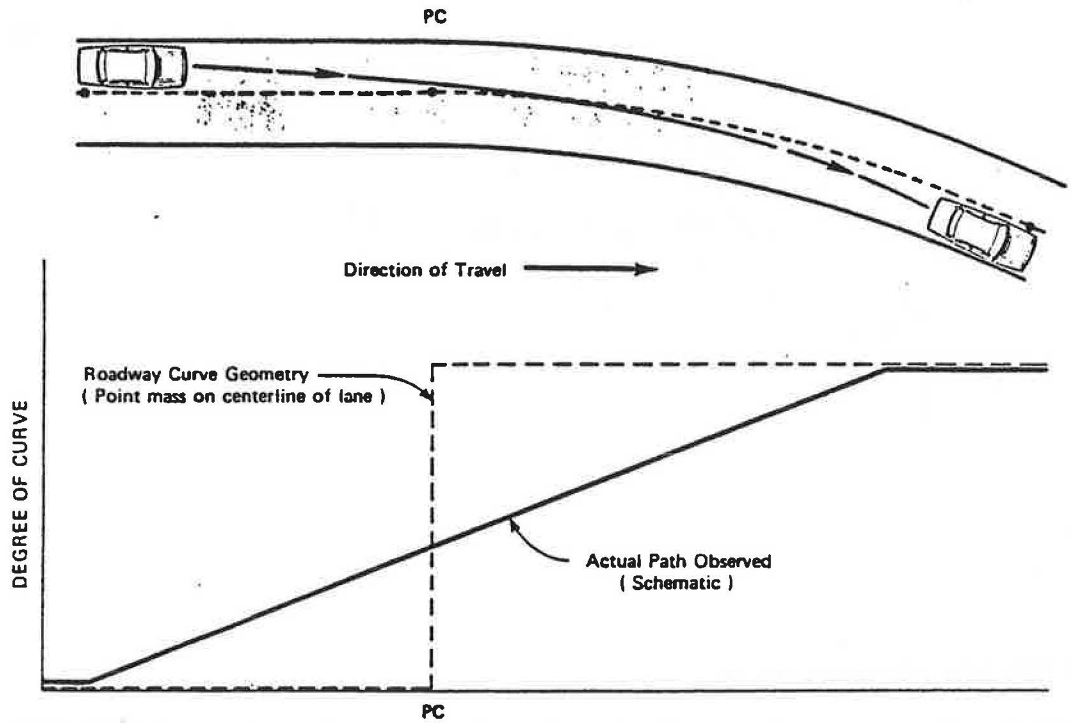


FIGURE 2 Comparison of observed, schematic path with centerline geometry (from Ref. 5).

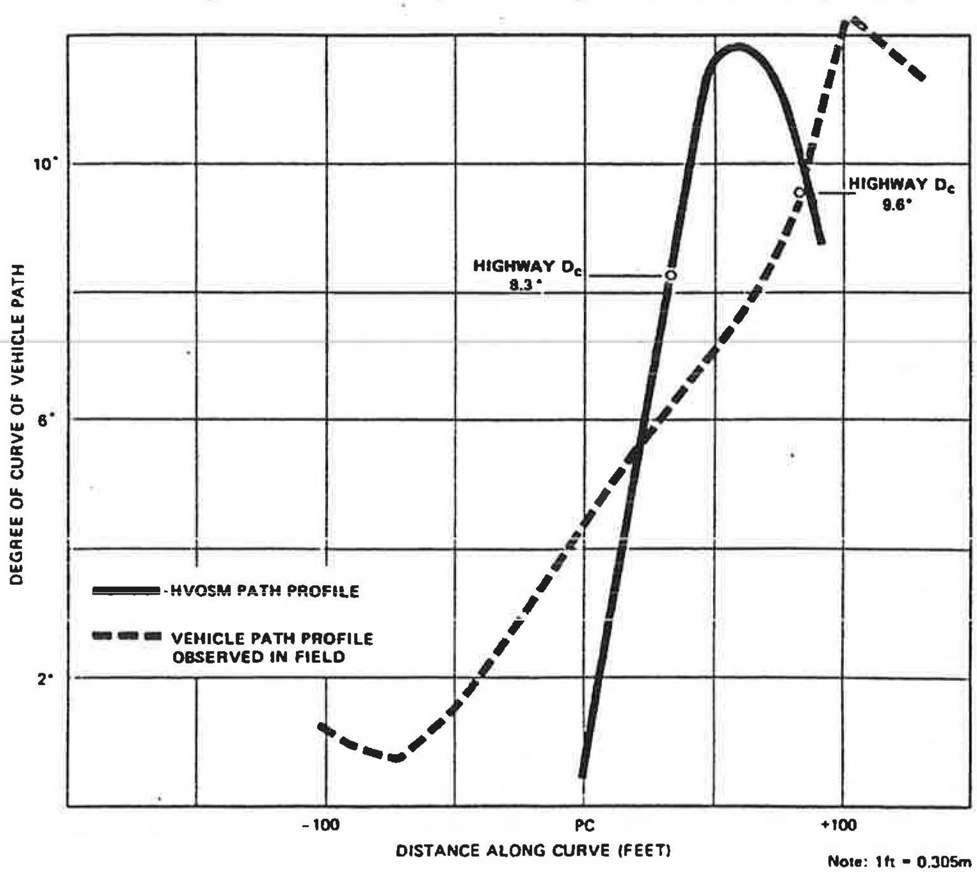


FIGURE 3 Comparison of vehicle path transitioning behavior from HVOSM and vehicle traversal studies (from Ref. 5).

HVOSM driver model was attempting to follow the specified centerline of the roadway and developed a more rapid rate of spiral, which developed after the PC. This discrepancy can be overcome in future studies by an alternative specification of the desired path to be more representative of the observed path and/or variation of the neuro-muscular filter of the wagon tongue to be more representative of the observed vehicle and driver characteristics.

The standard outputs from a typical HVOSM simulation run include the vehicle position, orientation, acceleration, tire forces, suspension forces and steer and camber angles. Additional output calculations added to the HVOSM during the JEL project were the driver "discomfort factor" and the friction demands of the individual tires.

The "discomfort factor" is representative of the resultant acceleration that an occupant experiences during a recovery maneuver (Fig.4). The use in the evaluation of cornering maneuvers of a hard mounted accelerometer measurement of lateral acceleration of the vehicle does not include the effects that the vehicle roll angle has on the occupant. For example, a vehicle in a normal cornering maneuver rolls in a direction opposite to the turn (i.e., rolls positive, or right for a left hand turn & visa versa) and therefore the "discomfort" which would be experienced is greater than the calculated lateral acceleration (i.e., V**2/R). Curves are superelevated to reduce or reverse the magnitude of the vehicle roll angle to reduce the "discomfort factor" felt by the driver and occupants. Many of the earlier geometric design criteria standards were based on experimental measures of a ball bank indicator during cornering maneuvers which essentially measured the same resultant acceleration as the HVOSM calculated "discomfort factor." The "discomfort factor" output of the HVOSM illustrated the problems associated with cross-slope breaks on highway curves in "HVOSM Studies of Highway Cross Slope Breaks on Highway Curves", (Ref.9) which was also prepared as a part of the JEL study. In that study the problems associated with cornering on an adversely super-elevated curve (i.e., cross slope break) were demonstrated by examination of the "discomfort factor." Subsequent recommendations were made to reduce excursions onto the shoulder break which can result in unacceptable levels of driver "discomfort."

The friction demand is another calculated variable that has been added to the HVOSM output (Fig.5). As a vehicle is steered into a turn, side forces develop at the tires which permit the vehicle to make the cornering maneuver. The amount of surface friction required to support a given cornering maneuver is defined as the

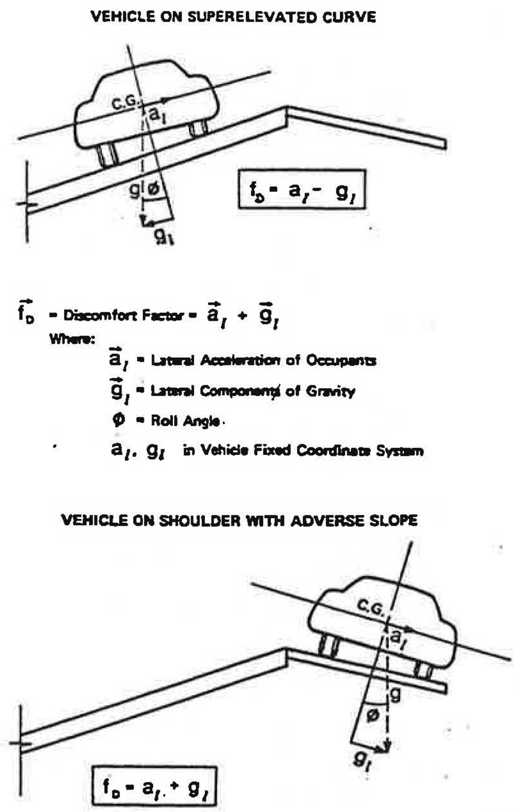


FIGURE 4 Relationship between driver discomfort factor and combination of roll angle and lateral acceleration (from Ref. 9).

"friction demand" which is equal to the ratio of the side force to the normal load for an individual tire. The standard output of HVOSM already included the individual tire side forces and normal loads so the output modifications entailed a simple calculation of the time-history of the cited ratio at each tire.

Another subtask of the JEL study included the use of both the HVOSM and the PHASE4 programs to evaluate passing maneuvers over centerline crowns (Ref 10)(Fig.6). The research included a direct comparison of the HVOSM and the PHASE4 programs to obtain a measure of the degree of correlation between the simulation models. The Phase4 program was modified to utilize the same driver model and terrain definition and interpolation routine as the HVOSM to implement the comparison. Since both programs can handle single unit trucks, inputs for a 1974 White Road Boss (4x2) were used for the comparison simulations (Ref 11). The results of the comparison of the programs demonstrated a generally good agreement of the predicted response characteristics of the two simulation programs for maneuvers such as a passing-type maneuver.

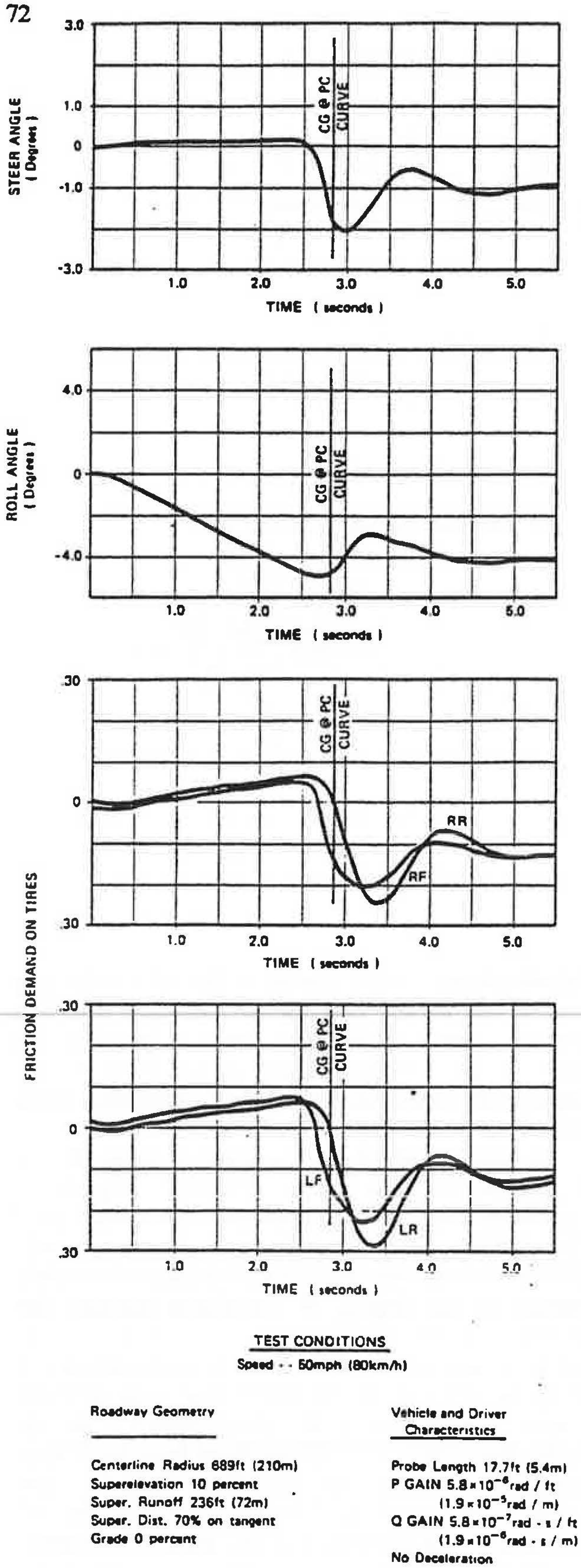


FIGURE 5 Sample HVOSM outputs (from Ref. 5).

In other research in the 1980's, Midwest Research Inc., included an application of HVOSM in their FHWA sponsored research on Work Zone Design Considerations for Truck Operations and Pavement/Shoulder Drop-Offs (Ref.6). In that study, the HVOSM was modified to include an enhanced tire model which simulated the tire sidewall interaction (i.e. scrubbing) that can occur in pavement/shoulder drop-off maneuvers. Early curb-impact research by Texas A&M (Ref.12) had revealed a degraded correlation of HVOSM with full scale curb impact tests for shallow encroachment angles which was later confirmed by follow up studies by McHenry, et al (Ref. 13) and Segal, et al

(Ref.14). The modification for the MRI project improved the modeling technique utilized for shallow angle encroachments and allowed the scrubbing interaction to be simulated for curbs as well as shoulder drop-offs. However, the generally fragmentary documentation of full scale test runs of pavement/shoulder drop-offs and shallow angle encroachments of curbs precluded a rigorous validation from being achieved. Of particular importance in this type of maneuver is the front wheel steering response immediately subsequent to the curb or pavement/shoulder mount.

A study performed for FHWA by Calspan in 1986 entitled "Rollover Potential of Vehicles on Embankments, Sideslopes and other Roadside Features" (Ref.7) included the application of HVOSM to predict the dynamic responses of vehicles encountering a variety of roadside-feature configurations. Enhancements to the HVOSM that were provided to Calspan by McHenry Consultants, Incorporated were the aforementioned refinements from the other projects as well as options to allow the modeling of deformable soil plowing, an enhanced tire model to improve modeling of the rollover phenomenon and a sprung-mass ground contact model to permit multiple rollovers to occur by simulating interactions between the vehicle structure and the terrain.

In 1985, the Highway Safety Research Center of the University of North Carolina (HSRC) conducted a study of Safe Geometric Design for Mini-Cars for FHWA (Ref. 8), which included among many other things the use of HVOSM to supplement an investigation of sideslopes and related issues, traffic islands and relationships between vehicle parameters and rollover propensity.

The findings related to sideslopes confirmed earlier work by Calspan (Ref.7). The finding with respect to traffic islands took the form of a "rollover envelope" defining a range of speeds in which a vehicle may roll over when impacting a traffic island.

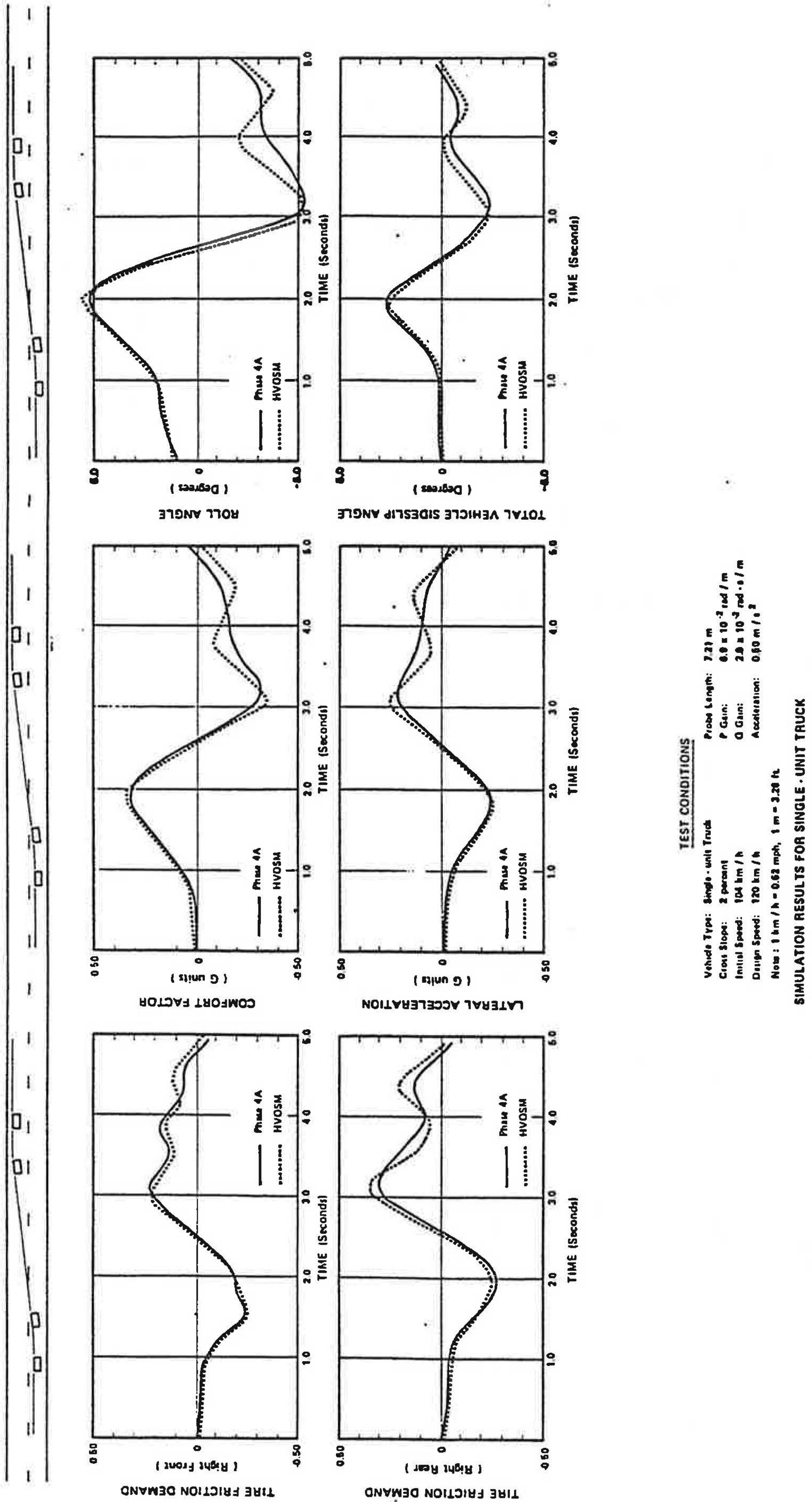


FIGURE 6 Comparison of phase4 and HVOSM simulation programs (from Ref. 5).

With respect to rollover propensity, many researchers have referred to the "static stability factor" (i.e., T/2H, T=track width, H=CG height) which is used as is a measure of a vehicle's propensity to roll over. HVOSM was used to test the merits of the equation. The HVOSM demonstrated the fact that the responses of a vehicle differ from these of a concrete block, and, therefore, the "static stability" factor is an oversimplification (Fig.7). A vehicle constitutes a dynamic system which combines inertial, tire and suspension properties as well as dimensional characteristics to define handling properties which can, under some circumstances, produce a rollover. There also appears to be a relationship between the inertial ellipsoid of a vehicle and the vehicle's rollover propensity when the tires suspension and dimensional properties are also considered. The exact relationship or a calculatable "factor" defining a vehicle's rollover has yet to be determined.

In summary, two very powerful and well documented vehicle simulation programs, HVOSM and the PHASE4, can be utilized to supplement investigations of the changing vehicular population and its effect on roadway and roadside geometric design requirements. Several applications of these programs performed in recent years have been briefly presented and discussed. The applications demonstrate the range of interactions between vehicle characteristics and roadway and roadside geometric design features which can be investigated by simulation techniques.

Relationship between Flat Surface $\mu_{CRITICAL}$ and Static Stability Factor (T/2H)

Vehicle	Total Weight (lb)	Mass (kg)	Flat Surface $\mu_{CRITICAL}$	T/2H	μ_{CRIT}/T/2H %
Ordered with respect to T/2H:					
Civic	1699	770	1.00	1.23	81%
Rabbit1	2410	1093	0.85	1.27	67%
Omni	2138	969	0.95	1.35	70%
Rabbit2	1800	816	0.95	1.37	69%
Malibu	3580	1624	1.15	1.40	82%
Celebrity	2974	1349	1.15	1.42	81%
Vega	2639	1197	1.25	1.46	86%
LTD	4450	2018	1.40	1.55	90%
Ordered with respect to $\mu_{CRITICAL}$:					
Rabbit1	2410	1093	0.85	1.27	67%
Omni	2138	969	0.95	1.35	70%
Rabbit2	1800	816	0.95	1.37	69%
Civic	1699	770	1.00	1.23	81%
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Celebrity	2974	1349	1.15	1.42	81%
Vega	2639	1197	1.25	1.46	86%
LTD	4450	2018	1.40	1.55	90%

Comparison of Critical Friction Coefficients for Rollovers for Various Vehicles Modified to Have Identical Static Stability Factors

Vehicle	Modified Sprung Mass CG Height (in)	(mm)	Static Stability Factor (T/2H)	Critical Rollover μ	% of $\mu_{CRITICAL}$/T/2H For T/2H = 1.30	For Original T/2H
Honda	-21.97	-558	1.30	1.10	85%	81%
Celebrity	-24.12	-613	1.30	1.00	77%	81%
LTD	-24.70	-627	1.30	1.17	90%	90%
Vega	-22.52	-572	1.30	1.05	81%	86%

FIGURE 7 Comparison of "static stability factor" with HVOSM simulated rollovers (from Ref. 8).

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Application of Expert Systems to Highway Geometric Design Decisions

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Abstract

Expert systems, also known as knowledge-based systems, are computer programs for interactive problem solving through the formal representation of the knowledge and procedures used by an expert in a particular field. There has been a growing interest in the application of expert systems to engineering design problems over the past few years. The development of sophisticated computer-aided design techniques and associated databases, together with powerful workstations with advanced graphics capabilities, has created both a suitable environment for such applications and the need for ways to improve the productivity and performance of the design process.

The paper introduces the structure of expert systems and provides an overview of the techniques used for knowledge representation and control of the inference process. The sequence of steps involved in the development of an operational expert system is described.

Although expert systems have not as yet been widely used in highway design practice, two experimental expert systems that address geometric design issues are described. The first provides advice on approach lane configurations for a signalized intersection, while the second uses design standards and site constraints to recommend horizontal and vertical alignment.

Finally, the paper examines potential future application for expert systems in geometric design, including route selection, interchange design, and reconstruction planning.

Introduction

Potential application of artificial intelligence techniques in general, and expert systems in particular, have been attracting increasing interest over the past few years in a wide range of fields, from medicine to finance. This interest has been stimulated by the increasing number of commercial hardware and software products designed for these applications, articles in the popular and professional press, and a growing number of specialized journals particularly in the area of expert systems.

Expert systems, also known as knowledge-based systems, are computer programs for interactive problem solving through the formal representation of the knowledge and procedures used by an expert in a particular field. They differ from conventional computer software in that the data structures containing the application knowledge and procedures are separate from the inference, or problem-solving, procedures, and not embedded in the program control code. This not only permits the knowledge to be extended once the expert system is in use, but allows the user to adapt the system to a particular problem through the addition of knowledge at run time. The structure of most expert systems also provides the user with an explanation of the reasoning process that led to any particular conclusion.

Although some of the earliest expert systems applications were in engineering, the development of civil engineering application has lagged somewhat behind some other branches of engineering. Even so, there is a growing interest in such application in both universities and the profession that has already resulted in a number of technical symposia, courses, conference sessions, journal articles, and research projects. These applications cover a wide range of civil engineering problems (1) and there is increasing experience with their use in operation (2).

The development of sophisticated computer-aided design techniques and associated databases, together with powerful workstations with advanced graphics capabilities, has created both a suitable environment for such applications and the need for ways to improve the productivity and performance of the design process. This paper addresses the potential role of expert systems in highway geometric design decisions.

The paper provides a brief overview of the structure of an expert system and the principal techniques used for knowledge representation and control of the inference process, as well as the sequence of steps typically involved in the development of an operational system. Although there has been very limited experience with the use of expert systems in highway design practice, two experimental expert systems that address geometric design issues are described. Finally the paper examines the potential for future applications of expert systems in the area of geometric design, including problems of route selection, interchange design, and reconstruction planning.

Overview of Expert Systems

Expert systems have been described above as problem solving computer programs based on the knowledge and procedure used by experts in a particular domain, or area of expertise. Although this description could also apply to many conventional computer programs, they differ from conventional software in a number of important ways. The most important of these are the way in which the knowledge is represented in the system and the separation of this knowledge from the inference process used to draw conclusions from the knowledge. Other differences commonly include the ability to explain the reasoning of the inference process to the user on request and the use of symbolic rather than numerical processing techniques. Symbolic processing, refers to the ability to work with knowledge expressed in word or textual symbols rather than numerical data.

The separation of the knowledge base from the inference, or reasoning, process and the use of symbolic processing result in a system that lends itself to an interactive environment, in which both knowledge of how to draw conclusions and the intermediate conclusions themselves can be stored in symbolic form and displayed to the user on request. This permits each step of the reasoning to be explained if required. It also provides a highly flexible way to store knowledge, allowing the user to introduce new knowledge at run time, without having to understand the internal structure of the software.

The architecture of a typical expert system consists of five components (Figure 1):

1. Knowledge base,
2. Context,
3. Inference mechanism,
4. Explanation facility, and
5. User interface.

The knowledge base contains facts and heuristics, or rules that guide how facts are to be interpreted and associated with the domain for which the expert system is designed. The context contains the facts that describe the current problem and any intermediate conclusions reached. The inference mechanism is the part of the expert system that performs the reasoning, using the facts and heuristics contained in the knowledge base, and the facts and intermediate conclusions contained in the context. As new conclusions are formed, the inference process stores them in the context. The explanation facility provides the capability to examine the contents of the context and knowledge base in order to describe the reasoning behind a particular conclusion.

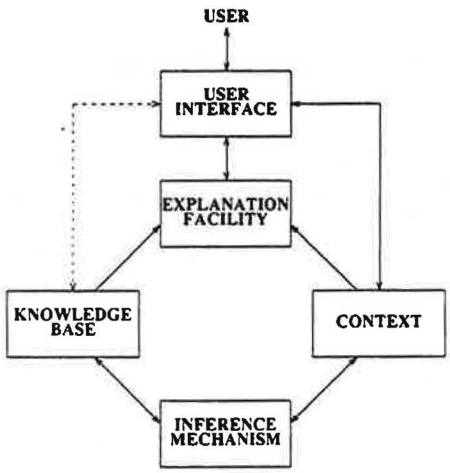

FIGURE 1 Expert system architecture.

This of course requires the inference mechanism to store appropriate information, in the context or elsewhere, to permit the reasoning to be reconstructed. The user interface provides the ability to present results to the user, receive user input, and allow the user to request explanations or select other features. The user interface may also provide a set of tools for the user to examine or modify the knowledge base.

Computer software containing each of these components, but no domain-specific knowledge, are known as shells. Expert systems can be created using such shells by adding the appropriate knowledge. Although expert systems can be, and sometimes are, written from first principles using a suitable language, in most cases it is much easier, faster, and less expensive to use an existing shell. A wide variety of expert system shells and development environments exist, with a corresponding range of features, capabilities, and prices. Selecting a appropriate shell will generally require careful analysis of the problem to be addressed. Comparative reviews of the features of different shells exist, for example, W.R. Wigan, *Knowledge Based Systems Tools on Microsystems* (3), but assessments of their suitability for particular types of application, such as that by Mullarkey (4), are much less common.

Knowledge Representation Techniques

A variety of knowledge representation techniques have been developed to encode knowledge in expert systems, of which the two most widely used are production rules and frames. Production rules consist of statements of the form: If (condition) then (conclusion).

The "condition" part of the rule may be a simple or complex expression, involving facts or other conclusions. When this condition is found to be true, then the "conclusion" is also held to be true.

For example, the following rule represents the minimum curb radius that can be used on a right angled turn for a WB50 design vehicle, if the rear wheels of the trailer are not to run over the curb (5):

If Design Vehicle = WB50
And Turn Angle > 90
Then Min Curb Radius = 19.8

A frame consists of a structured representation of knowledge about a particular class of object or concept. It includes a defined set of properties for that concept, usually termed slots, with associated values which may consist of pointers to other frames or procedures, sometimes called daemons, that compute values when required or under specified circumstances. A very common type of pointer in a frame is the slot "type-of." Thus, a frame containing knowledge about an arterial highway may have a "type-of" slot pointing to a road frame. This allows the arterial frame to inherit properties of roads in general from the road frame. A separate frame is created for each instance of a particular concept.

Figure 2 illustrates a frame that might be defined for a highway alignment expert system. The frame describes the properties of a circular curve. Each such curve is identified with an ID slot (in this case curve 153), and is an instance of a more general entity termed a segment. The three slots for the intersection point (IP) and points on the two tangents (tan1, tan2) contain pointers to other frames (of type point), where the coordinates of the points, and possible other data, are stored. This permits the position of a point to be changed in the point frame, and the effect of this change to be automatically incorporated in all related frames, such as this curve. The radius of the curve is defined by the value of the radius slot. However, since the intersection angle (IA) and length of the curve (length) are now uniquely defined by the other data, these slots contain daemons that compute these values whenever they are required.

FRAME	CURVE
ID	153
TYPE_OF	SEGMENT
IP	POINT.H7
TAN1	POINT.H6
TAN2	POINT.H8
RADIUS	600
IA	Proc1
LENGTH	(IA*RADIUS)

FIGURE 2.

The IA daemon is a defined procedure (proc1) that computes the angle from the locations of the intersection and tangent points. The length daemon is a symbolic expression that is evaluated using the current values of the IA and radius slots. Note that a call for the value of length will in turn call for the value of IA, which will in turn fire proc1, which will in turn call for the values of slots IP, tan1, and tan2, which will in turn call for the current values of the appropriate slots in the point frames for the points H6, H7, and H8. If any changes have been made in the current position of these points, this will be incorporated in the length of the curve.

Less commonly used techniques include semantic networks and scripts. Semantic networks represent the connectivity between pieces of knowledge. Nodes in the network represent information, while links represent relations between those pieces of information. The nodes are labelled with the particular information and the links with the nature of the relationship. While this lends itself well to graphical representation, its implementation in a requires additional structure. A script is a structure that describes a defined sequence of events or activities in a particular context. These events form a causal chain, in which earlier events allow later events to occur. Associated with these events are conditions that must hold for the events to occur and slots representing people and objects involved in the events. Scripts can be used to reason about how different events relate to each other. Although scripts have not yet been applied to engineering problems, one could imagine their use in highway safety analysis, in which an expert system might reason about driver behavior.

Analytical models provide another form of knowledge representation, including both factual and procedural knowledge. Because of their importance in solving engineering problems, the development of techniques for model-based reasoning in expert systems is an area of strong current interest.

Uncertainty in both facts and the results of inference are a common aspect of most real world problems. A number of techniques have been developed for handling uncertainty in expert systems. In addition to the classical approach of Bayesian probability theory, less restrictive methods have been developed. One common approach is to assign certainty factors to each fact and conclusion. These are numbers between zero and 100, or zero and one, where low numbers indicate a fact is very uncertain and high numbers that it is quite certain. Rules have been developed to compute certainty factors for conclusions drawn from facts or other conclusions of differing certainty. Other approaches have been based on fuzzy set theory.

In developing a knowledge base for a particular application in highway engineering, it would be highly desirable to do so in a format that is suitable for subsequent development of additional applications, since so much of the required knowledge is common to different problems. While the exact syntax of production rules, implementation of frames, or interface with analytical models will depend on the particular shell being used, extensibility of knowledge bases will be enhanced by:

a. Preserving generality and
b. Making use of higher-level concepts, sometimes referred to as meta-knowledge.

Rule generality can be preserved by the explicit incorporation of parameters that are assigned values for a particular application by other rules in the knowledge base. For example, an expert system for the design of two-lane rural highways could incorporate geometric rules for multi-lane facilities, expressed in terms of the number of lanes, with an application specific rule setting the number of lanes to two. Although this will increase the complexity of the rules, it will simplify extension of the knowledge base to other types of problems. The use of high-level concepts, such as safe braking distance, can be used to simplify rule structure and increase generality. Lower-level rules are then used to determine the safe braking distance for a specific situation. By uncoupling the concept from its specific application, both the higher-level and lower-level rules may be used in other applications.

Inference Mechanisms

Inference mechanisms provide the control that determines the order in which the knowledge in the knowledge base and context will be used in attempting to solve a problem. The two basic approaches are forward chaining and backward chaining. Forward chaining, or data driven reasoning, proceeds from the initial facts in the context to intermediate conclusions, and hence progressively to a solution. Backward chaining, or goal directed reasoning, begins with a possible solution, or goal and progressively examines the condition that must be true in order for this solution to be valid. As each condition is identified, it in turn will require other conditions or facts to be true for it to hold. The inference thus works back to the initial conditions. If the inference process establishes that a required condition is not true, then another solution or goal is selected and the process is repeated.

These two approaches are illustrated in Figure 3, which indicates various sets of possible initial conditions (C1 to C4), three possible goals (G1 to G3), and intermediate conclusions (S1 to S7). With forward chaining, if it is found that C1 is true, then it would be concluded that S1 is also true. This in turn would imply that S4 and S5 are true, and hence that goals G1 and G2 are satisfied. Conversely, with backward chaining, if it is desired to determine whether goal G3 is satisfied, it would be determined that either S6 or S7 must be true. This in turn implies that either S2 or S3 must be true, which will be satisfied if initial conditions C2 or C3 or C4 are true.

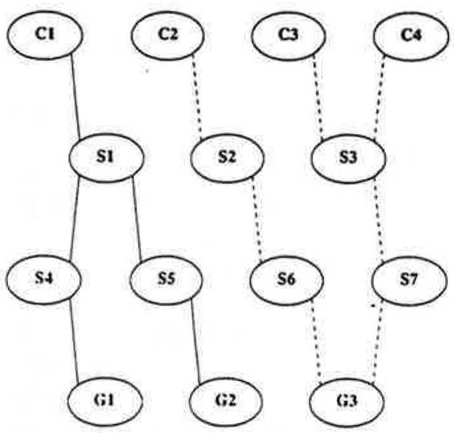

FIGURE 3 Search strategy.

At each stage in the reasoning there will generally be many facts that are true or several conditions that need to be satisfied. After the implications of a particular fact have been determined, the reasoning process can proceed to examine the implications of one of the new facts, or can back up to examine the implication of one of the other facts already established. The former approach is termed a depth-first search, while the latter is termed a breadth-first. In Figure 3, a depth-first strategy, after determining that S1 is true, would then determine that S4 is true and hence G1 is satisfied, before determining that S5 is also true and hence G2 is satisfied. A breadth-first strategy would first determine that S4 and S5 are true before determining that these in turn imply that G1 and G2 are satisfied. Similarly, a backward chaining, depth-first strategy would search up the tree from G3 to C2, before examining whether S7 is true, while a breadth-first strategy would proceed up the tree one level at a time, determining all the higher-level intermediate conclusions that would need to be true for the lower-level conclusions to be satisfied.

Thus there are four possible reasoning strategies, based on a combination of forward or backward chaining with depth-first or breadth-first search. Most simple expert systems are based on one of these four strategies. More sophisticated inference mechanisms allow combinations of these strategies, with higher level rules, termed meta-rules, to direct which strategy is applied in a given circumstance.

The foregoing approaches require a decision about the truth of a particular condition to be made at the time the condition is examined. In some application this is a disadvantage, since the condition may be affected by other conditions not yet examined. Consider the problem described by Rich (6) of selecting officers for an association. The factors affecting the choice of secretary will be influenced by who is selected as chairman, and of course one cannot select the same person for both posts. One could select the chairman first, but by the same token, the choice of chairman is influenced by who is going to be secretary. This type of problem can be addressed by constraint-directed reasoning. Constraints are posted using variables that are not assigned values until a decision is necessary about the value of a particular variable. At that time, all other constraints that include that variable can also be examined.

The Expert System Development Process

The process of developing expert systems has received considerable attention in the literature, and is well described by Hayes-Roth et al. (7). Some of the issues that arise in the implementation of expert systems are discussed by Dym (8). The following discussion provides an overview of the process, which can be considered to consist of six steps:

1. Problem definition,
2. Knowledge acquisition,
3. Selection of knowledge representation and inference techniques,
4. Prototype development,
5. Field testing, and
6. Operational development.

The problem definition stage lays the groundwork for what is to follow. It is obviously important that the problem the expert system is to address must be well defined. It is equally important to define the goals of the project. Is it to solve an existing problem that is not currently well handled or to gain experience with expert systems? If it is the former, in what ways are existing approaches inadequate? If the latter, it is important to select a problem that is complex enough to be interesting, while still being achievable in a reasonable length of time with the resources available. It is important to consider who has the knowledge to address the problem, and whether they will be available to provide it in the detail required.

Knowledge acquisition involves the identification, extraction, and recording of knowledge that will be used in the expert system. Some of this knowledge will already exist in a formalized way in manuals, procedures, textbooks, and so forth, but this alone will generally be insufficient and will need to be supplemented by the heuristic rules developed through experience by experts in the domain. Unfortunately, experts will rarely be able to respond effectively to the request to "Tell me what I need to know." It is up to the expert system builder to explain to the experts what is needed. This will require involving the experts in the design of the expert system. Knowledge acquisition techniques that have been found to be effective include working through sample problems, analyzing case studies, videotaping experts performing their jobs, and evaluating the results of early versions of the expert system. The knowledge acquisition process is not a one-step activity, but must be integrated into the development and testing.

Once a preliminary knowledge base has been assembled, the appropriate knowledge representation and inference techniques must be selected. In practice, this often translates into selecting an appropriate shell, although some of the more sophisticated development systems permit a variety of knowledge representation and inference techniques. While some choices are largely dictated by the nature of the problem, others will only become clear through experience in trying alternative approaches.

The next step is usually the development of a laboratory prototype. This is the stage which many expert system projects have reached to date. It is generally advisable to approach this development incrementally, starting with simple problems and a small knowledge base, and addressing progressively more difficult problems as experience is gained. This allows feedback and further input from the domain experts.

Once the prototype development has reached the point at which the expert system appears to be capable of tackling genuinely interesting problems and producing useful results, the next stage is to test it in an operational environment. This exposes the system to the full range of situations encountered in the real world, and provides the opportunity for operations personnel to provide feedback on how useful the system appears to them. Such field tests should be carefully conducted in order to ensure adequate monitoring of the situation and system performance, so that failures can be thoroughly analyzed and success rates determined. If serous problems emerge during the field test, it may be necessary to suspend testing while they are fixed, and then conduct additional series of tests later.

The final stage, operational development, consists of a cyclical process of system enhancement and operational experience. With increasing experience, the need for enhancements will be identified, although the system may be performing a useful function. Responsibility for identifying these needs will shift from the system developers to the users, as the users gain familiarity with the system, and the system developers will assume more of a support role.

Examples of Applications to Geometric Design

There have been relatively few applications to date in the area of highway geometric design, although there are a growing number of applications in related areas, including noise barrier design (9), construction planning (10), and pavement management (11).

The following paragraphs describe two experimental expert systems that have been developed by university researchers that address geometric design issues. As further experience is gained with these and other systems, particularly operational experience applying them to real problems, more will be learned both about the usefulness of expert systems and techniques for applying them to geometric design problems.

Intersection Advisor

Intersection Advisor is a prototype expert system that has been developed in the Civil Engineering Department of North Carolina State University to recommend geometric modifications to improve intersection operation (12). The system requests information from the user on traffic volumes, critical movements, approach lane geometry, and constraints to geometric improvements, then recommends the most efficient improvements for each approach.

The system was developed using a commercial expert system shell based on production rules and a backward chaining inference process and designed to run on personal computer. Based on the approach volumes and turning movements, the system selects an initial ideal approach configuration that provides a balanced volume/capacity ratio for all lanes. The system then invokes a set of constraint rules that check whether the design violates any restrictions the user may have placed on the approach configuration, and if so, selects the next best configuration as the recommended design. Finally the system invokes a further set of rules that compare the recommended design and the existing situation and identify a specific set of modifications to improve the intersection approach.

Road Lab

This system has been developed in the Architecture and Planning School at the Massachusetts Institute of Technology as a tool to design road layouts for site planning (13). The specification for the recommended layout emerges from the application of successive constraints, such as the need to avoid designated areas, to link specified points, or to align along view corridors. Additional constraints can be specified reflecting design standards that restrict horizontal and vertical curvature and allowable gradients. These constraints then guide the conceptual design.

Numerical values within the specification have an initial uncertainty, limited with upper and lower bounds. This provides the flexibility to develop a design within the constraints. The use of symbolic expressions in the constraints avoids the need to specify whether a given variable is independent or dependent.

The system identifies a set of points that define a horizontal and vertical alignment that attempts to satisfy all the imposed constraints.

Potential Future Applications

While highway geometric design involves a large amount of algorithmic computation and the application of basic design criteria and standards, the selection of a potential configuration to analyze is not primarily a matter of numerical calculation, but involves the use of engineering judgement in balancing many different factors, including site-specific conditions and cost and environmental considerations. This type of problem would appear suitable for the application of expert systems, provided the knowledge base is rich enough to span the issues of concern. By linking such systems with more conventional highway design packages and CAD software, it should prove possible to increase the effectiveness with which the latter are used.

In addition to further development of the two systems described above, there appear to be many other areas that deserve examination. These include the interaction of geometric design knowledge with traffic engineering techniques, including appropriate signing, speed or passing restrictions, and safety implications of design features generally. The following paragraphs describe three particular applications that illustrate areas where expert systems may be able to enhance conventional techniques.

Route Selection

The choice of route for a highway within a broadly defined corridor involves consideration of wide range of issues, including:

- Horizontal and vertical alignment,
- Terrain and land use constraints,
- Economic factors, and
- Aesthetic considerations.

The choice of alignment must take into account constraints imposed by existing facilities, although these can often be modified, at some cost, if the need is strong enough. Frequently the most suitable land from the standpoint of terrain has already been taken by other uses that are not compatible with proximity to a highway. Thus there may be trade-offs between the cost of construction and use on the one hand, and effect on adjacent land uses on the other. As undeveloped land and open space becomes increasingly scarce, the need to balance all these factors in the light of local circumstances will become ever more important.

The ability of expert systems to reason with both symbolic and numerical information would appear to be particularly suitable to problems of this type.

Interchange Design

Fitting freeway interchanges into an urban environment can present difficult design challenges, particularly where existing highways are being upgraded to handle higher traffic volumes. Ramp geometry can be highly constrained by the interaction of design standards and the need to link to existing facilities. Site constraints may further reduce flexibility, and may conflict with design standards. Traffic flow patterns may impose other constraints, including the need to provide queueing space and sufficient lane capacity. Finally, structural requirements have to be satisfied.

As with route selection, developing a suitable configuration requires the ability to balance a range of both quantitative and qualitative factors. Equally important is the need to be sure that important constraints have not been overlooked. This area would also seem to be appropriate for an expert systems approach.

Reconstruction Planning

The need to rehabilitate existing highway facilities at the same time as accommodate growing traffic volumes will present difficult planning problems for those responsible for planning construction activities. Construction sequencing will need to be carefully integrated with the provision of temporary routes to relieve traffic congestion and provide adequate work space. Projects will have to be carefully phased to minimize the affects and ensure that traffic disruption caused by one project does not compound the problems caused by another.

The application of expert systems to problems of this type is already receiving considerable attention in the area of construction management. However, it is likely that the special requirements of highway projects, in particular the need to continue to handle the traffic during the work, would justify the development of systems to address these specific problems.

Conclusion

Expert systems are beginning to emerge from the laboratory and enter civil engineering practice, addressing a wide range of problems. By formalizing what we have come to term engineering judgement, they can provide a way to combine this knowledge with more conventional numerical computing and access to large databases and CAD systems opening the prospect of highly intelligent support systems for engineering design and planning.

Although relatively few applications have been developed so far for highway geometric design, there appears to be considerable potential for expert systems to play a significant role in the future. As with any computer tool, expert systems are no smarter than those who design them and cannot take account of factors that they have not been designed to address. On the other hand, they cannot forget or overlook something that has been included. While early expert systems are likely to be somewhat naive, and perhaps only useful as a training tool, continued refinement and development should produce systems of considerable sophistication, that can assist engineers in weighing the many factors that affect highway geometric design decisions by drawing attention to potential problems and suggesting solutions.

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The Use of CADD Systems for Highway Design Evaluation

By: William J. Wiedelman, P.E., Project Manager, Howard, Needles, Tammen & Bergendoff, Indianapolis, Indiana.
The author was affiliated with Mid States Engineering, Inc. during the preparation of this paper

Introduction

Computer Aided Design and Drafting (CADD) development has produced a revolutionary capability to store and retrieve data on highway characteristics. This data, when combined with analysis software, can provide transportation engineers with new opportunities for evaluating both proposed design features and existing highway features. Computer graphics systems currently have two primary applications in transportation engineering; Geographic Information Systems (GIS) and CADD systems. GIS application include database queries and reports on roadway characteristics such as accidents, traffic classification, and so forth. CADD applications typically have concentrated in the areas of topographic mapping and contract plan preparation. The integration of database files with typical graphics files provide efficient access to information which previously required considerable effort to assemble for project studies. The complete integration of highway information systems and drafting systems is still only a concept to be developed. However, the use of graphic files and databases currently being produced can now be used in the highway design evaluation process.

The Basics of CADD Systems

Computer application software for transportation system analysis typically ignores the existence of both GIS and CADD technology. The proliferation of microcomputers and subsequent software development has created diverse software formats. The days of all programs being written in FORTRAN using card images for data input are long gone. Different programming languages, graphics drivers, and software shells have all contributed to the expansion and disarray of application software.

CADD systems are frequently only thought of in terms of drafting applications. However, CADD graphics files can also serve as a common database for application software and graphic displays. The use of a CADD system for application software development builds on a core of knowledge and grows with it, rather than generating independent programs.

Application Software Development

Although a high degree of computer sophistication may be required to generate application software for use with CADD systems, the benefits may far exceed the expenditure of time and effort. The benefits are different from the typical gains in drafting productivity normally associated with CADD applications. The use of CADD to store large amounts of graphical data can create new opportunities for evaluating proposed designs as well as existing highways. Transportation engineers now have the ability to store, retrieve, and analyze an almost limitless amount of data utilizing the new computer tools available.

Intergraph has provided, through their open architecture of the Interactive Graphics Design System (IGDS), the capability to store user-defined data within the graphical file. The user data area can be configured for each element to store pointers to other elements, identification numbers and user application data. The user data is accessible through application programs for use in computations, display, and plotting. Menus can be created to input and modify the data in a user friendly environment. The use of database inquiries can supplement the graphic data to provide access to GIS database information.

Typically the highway design process is an interactive one in which traffic service requirements are defined within a transportation planning effort and refined as design alternatives are developed. The operational effects of design features are analyzed together with environmental impacts, construction costs and staged construction. The final design evolves as a compromise between project constraints and requirements. It is during this important design evaluation stage of project development that many features of highway design are analyzed, and when the design process can achieve a high level of design excellence or fail to produce the best result.

Design Evaluation Criteria

In addition to standard highway design criteria, there are factors which impact the design quality with respect to operational characteristics. The effect of highway design elements on traffic operations may not fall within defined standards, but are subject to engineering judgement and compromise. The goal of improved design techniques and computer aided design, should be improved decision making based on more efficient and comprehensive analysis. The overall evaluation of a project design is a dynamic process, changing by location as geometry and traffic change. The graphical display of performance criteria, such as level of service, sight distance, cross section, accident rates, ramp terminal characteristics, and operating speeds can highlight areas where a combination of design weaknesses are a significant problem

Example Applications

Design Speed and Operating Speed

Both design speed and operating speed are directly related to the horizontal and vertical alignments. The evaluation of these operating characteristics and graphical display of the results is an important component of the evaluation of an existing condition or selection of proposed alignment. The combination of traffic volume database, together with the graphical design elements, provides the information to identify design and operating speeds. This evaluation is applicable to the evaluation of existing highways based on new design speed standards or the development of new designs.

Sight Distance

The evaluation of existing roadway sections and proposed design includes the consideration of appropriate sight distances. The determination of passing sight distance on two-lane highways is necessary for proper pavement markings and signage. Passing sight distance is also important for an operational analysis of the opportunities available for vehicles to pass considering the effects of grade and traffic volumes. Stopping sight distance is a primary design element of multiple-lane highways. Although design criteria for vertical curves and horizontal obstructions include stopping sight distance and cross section features, high conflict locations still need to be considered. Ramp terminals and intersections have special requirements for stopping sight distance and decision sight distance.

The Green Book suggests the measurement of sight distances at each alignment station for both directions of travel. It also describes a manual procedure using templates on plan and profile views to identify available passing or stopping sight distances. Although the manual procedure is a straight forward method, it is time consuming when evaluating multiple alternatives or many miles of highway. Also, the analysis of sight distances should be performed several times during a project as cross-section details are developed and sight distance obstacles become known.

The current procedures for utilizing CADD in the design process generates graphical horizontal alignment, vertical alignment, and cross sections. In other words, graphical data files are typically produced which contain the information needed to analyze sight distances. The process a designer follows to identify sight distances using a template, is largely one of visual interpretation. Approximate points of tangency and intersection can be found easily by rotating the template until the sight line intersects a horizontal obstruction or grade line. Although modeling this simple human task by computer requires a large amount of data and computer processing, the advent of CADD and relatively low cost computer processing has made performing these tasks by computer practical.

Capacity Analyses

Application programs such as the *Highway Capacity Software*, January, 1987 sponsored by the Federal Highway Administration, utilizes many data files for storing set-up data and intermediate calculations. The sharing of data between CADD systems and other application programs requires a direct program translator or a common data transfer file. Most application programs have not and are not being written with the concept of data transfer to other systems. The user is therefore forced to decode the data file structure in one program in order to transfer data to another system. Data store in the CADD system, such as grades, traffic volumes, number of lanes, lane widths, and so forth can only be transferred to other application programs with significant programming effort. It is hoped that future program development and documentation will consider the need for data structures which are accessible to users.

Summary

The use of CADD systems as a tool for evaluating highway designs requires significant software development, but can produce benefits worth the effort. Application program development should be encouraged to include data transfer capabilities for both input and output. The integration of analysis programs with the CADD environment is greatly simplified when data can be shared between programs.

The development of special application software for a specific CADD system can have significant benefits for the design engineer and should not be overlooked. The traditional uses of CADD systems for mapping and drafting application should not deter the design engineer from developing his own application programs. Just as spreadsheets and database management programs have enhanced computer usage, a CADD package provides new tools for the engineer to use the computer effectively.

Economic Evaluation Models

By: Mark J. Wolfgram, Ph.D., Chief,
Economic Policy and Analysis,
Wisconsin Department of Transportation

Introduction

Economic analysis is an important highway planning tool at the Wisconsin Department of Transportation. Cost-benefit analyses are used to evaluate alternative system plans, establish priorities for major highway projects, and are required of all reconstruction projects before programming. Also, life cycle cost information is developed to support pavement design decisions and the rehabilitation of high cost bridges.

In the last several years, a number of economic evaluation tools and studies have been developed by the Wisconsin Department of Transportation. Three that will be discussed here include:

1. Life cycle cost analysis for pavements,
2. Accident evaluation, and
3. Speed and operating cost estimation.

Life Cycle Cost Analysis for Pavements

There were four major objectives in developing life cycle costing software. First, the software should be easy to use. Second, it should be flexible enough to accommodate a wide range of cost profiles over time. Third, the program should be easily updated. And finally, the output of the program should provide direct documentation of pavement design reports.

The program was developed in a Lotus 1-2-3 environment. It can analyze up to ten design alternatives and allows inclusion of both initial construction and as many as six rehabilitation activities. Maintenance cost patterns can be varied over the period of analysis. The discount rate, analysis period and the service lives of alternative pavement treatments can be varied to facilitate evaluation of the sensitivity of results to input assumptions. The model provides results in terms of both equivalent uniform annual costs and the present value of costs. Output produced by the model is shown in Table 1.

The model was implemented by replacing a less rigorous analysis procedure in the Wisconsin Department of Transportation's *Facilities Development Manual*. Training sessions were conducted in district offices in order to familiarize highway designers with the program. Output from the program is now a required part of all pavement design reports.

TABLE 1 OUTPUT FORM THE LIFE CYCLE COST ANALYSIS PROGRAM

1. Geometric Changes: Type in a project description here.

Geometrics:	Pavement	Shoulder	Passing
Highway Design Type A	22	3	40
Highway Design Type A	24	6	60

2. Traffic:

Completion year	
Average Daily Traffic (ADT) is	1220
Ten years after completion	
ADT will be	1440
Twenty years after completion	
ADT will be	1660

3. Analysis Period:

First year of Analysis period	1991
Length of analysis period (years)	40
Project Completion year	1991

4. Discount Rate: The discount rate is 5 percent (Wisconsin Department of Transportation standard discount rate is 5 percent).

5. Conclusions: Changing a highway from type A to type B will result in the following:

	Accident Rate	Annual Accidents Per Mile	Annual Accident cost Per Mile
Highway Design Type A	161	0.72	$5,970
Highway Design Type B	76	0.34	$2,802

LIFE-CYCLE COST ANALYSIS OF ALTERNATIVE PAVEMENT DESIGNS — STATE OF WISCONSIN/DEPARTMENT OF TRANSPORTATION

Date: 05-Sep-88

Project Description ===> Project number: 0616-41-00
Project Road I.D.: Cross Plains Reconstruction
Project Section I.D.: Middleton-Cross Plains
Project Route I.D.: USH 14
Counties: Dane

Parameters for the Analysis

Current Year: 1988
Analysis Period (yrs.): 50
Discount Rate: 5.00%

Specifications

Project Cost or Cost Per Mile (specify): Cost Per Mile
Number of Alternatives Analyzed: 4

Notes on the Analysis: The highway project, pavement designs and pavement costs are all fictitious in this analysis. The analysis is intended to demonstrate some of the capabilities of the analysis procedure. Note that under alternative #3, initial construction is delayed for five years. Under alternative #4, construction of the bituminous pavement is staged. Also note that the cost of maintaining the existing pavement under alternative #3 is quite high due to its deteriorated condition.

	Alternative #1	Alternative #2	Alternative #3	Alternative #4
Brief Description of Pavement Design ===>	PCC	Bituminous Plant Mix	PCC - Initial Construction Delayed	BPM - Staged Construction
Pavement Layer Design (# of inches)				
Portland Cement Concrete	8.00		8.00	
Bituminous Concrete		5.00		4.00
Bituminous Base Course				
Asphalt Stabilized Base Course				
P.C. Stabilized Base Course				
Untreated Gravel or Crushed Stone Base Course	6.00	15.00	6.00	12.00
Granular Subbase Course				
Other:				
Other:				
Total Pavement Thickness	14.00	20.00	14.00	16.00
Initial Construction				
Initial Construction Cost	278,000	211,500	278,000	205,000
Year of Initial Construction	1988	1988	1993	1988
# of Years Before First Rehabilitation	26	15	26	10
Pavement Rehabilitation				
Cost of First Rehabilitation	84,700	70,000	84,700	90,000
# of Years Before Next Rehabilitation	12	10	12	10
Description of Rehab. Activity	Resurface 3"	Resurface 2"	Resurface 3"	Resurface 4"

FIGURE 1 *(continued on next page).*

	Alternative #1	Alternative #2	Alternative #3	Alternative #4
Cost of Second Rehabilitation	75,000	75,000	75,000	75,000
# of Years Before Next Rehabilitation	10	8	10	10
Description of Rehab. Activity	Recycle	Recycle	Recycle	Recycle
Cost of Third Rehabilitation	75,000	90,000		75,000
# of Years Before Next Rehabilitation	8	10		8
Description of Rehab. Activity	Recycle	Recycle		Recycle
Cost of Fourth Rehabilitation		75,000		75,000
# of Years Before Next Rehabilitation		8		8
Description of Rehab. Activity		Recycle		Recycle
Cost of Fifth Rehabilitation				75,000
# of Years Before Next Rehabilitation				6
Description of Rehab. Activity				Recycle
Cost of Sixth Rehabilitation				
# of Years Before Next Rehabilitation				
Description of Rehab. Activity				
Salvage Value, Terminal Value				
Salvage Value at End of Service Life	0	0	0	0
Terminal Value ($ Value or Letter A)	A	A	A	A
Maintenance Costs				
Before Initial Construction				
Cost During First Year (Base Year Cost)			1,500	
# of Years w/ Base Year Cost			1	
Annual Increase in Maint. Cost (in $'s)			200	
After Initial Construction				
Cost During First Year (Base Year Cost)	0	0	0	0
# of Years w/ Base Year Cost	4	2	4	2
Annual Increase in Maint. Cost (in $'s)	50	50	50	75
After First Rehabilitation				
Cost During First Year (Base Year Cost)	0	0	0	0
# of Years w/ Base Year Cost	2	2	2	2
Annual Increase in Maint. Cost (in $'s)	50	50	50	50
After Second Rehabilitation				
Cost During First Year (Base Year Cost)	0	0	0	0
# of Years w/ Base Year Cost	2	1	2	1
Annual Increase in Maint. Cost (in $'s)	50	50	50	50
After Third Rehabilitation				
Cost During First Year (Base Year Cost)	0	0		0
# of Years w/ Base Year Cost	2	1		1
Annual Increase in Maint. Cost (in $'s)	50	50		50

FIGURE 1 *(continued on next page).*

	Alternative #1	Alternative #2	Alternative #3	Alternative #4
After Fourth Rehabilitation				
Cost During First Year (Base Year Cost)		0		0
# of Years w/ Base Year Cost		1		1
Annual Increase in Maint. Cost (in $'s)		50		50
After Fifth Rehabilitation				
Cost During First Year (Base Year Cost)				0
# of Years w/ Base Year Cost				1
Annual Increase in Maint. Cost (in $'s)				50
After Sixth Rehabilitation				
Cost During First Year (Base Year Cost)				
# of Years w/ Base Year Cost				
Annual Increase in Maint. Cost (in $'s)				
Other Life Cycle Costs				
Cost #1 (Before Initial Construction)				
Year of Occurence				
Description:				
Cost #2 (After Initial Construction)				
# of Years After Initial Construction				
Description:				
Cost #3 (After Initial Construction)				
# of Years After Initial Construction				
Description:				
Cost #4 (After Initial Construction)				
# of Years After Initial Construction				
Description:				
Life Cycle Cost Analysis Results				
Present Worth of the Costs				
Initial Construction Costs	278,000	211,500	217,820	205,000
Rehabilitation Costs	42,777	83,010	27,867	120,567
Maintenance Costs	5,880	4,017	12,666	3,660
Other Life Cycle Costs	0	0	0	0
Terminal Value (Subtracted)	4,905	818	1,962	2,180
Total Facility Costs	321,752	297,710	256,392	327,048
Equivalent Uniform Annual Costs				
Initial Construction Costs	15,228	11,585	11,931	11,229
Rehabilitation Costs	2,343	4,547	1,526	6,604
Maintenance Costs	322	220	694	200
Other Life Cycle Costs	0	0	0	0
Total Facility Costs	17,625	16,308	14,044	17,915

FIGURE 1.

Accident Evaluation

This study began when someone asked the question, "If we improve the geometrics on this road, what can we expect in terms of accident reduction?" A detailed analysis was undertaken of the relationship between highway geometrics and accident experience. The study included accidents that occurred on two-lane rural roads in Wisconsin over a period of five years. Animal and intersection related accidents were excluded.

Strong statistical relationships were developed linking accident rates to pavement width, shoulder width, the percent of the highway section where passing is allowed, and average daily traffic. Accidents were found to decrease with wider pavement, wider shoulders, and greater passing opportunities. Accidents increased with traffic. These results are summarized in a report entitled *Rural two-Lane Highway Accidents and Geometrics: A Statistical Analysis*. Example results are shown in Figures 2 and 3. Each figure demonstrates the effect of increasing shoulder width and traffic on mobility (non-animal and non-intersection related) accidents. The effect of pavement width can be seen by comparing rates between Figures 2 and 3 for roads with similar shoulder width.

A Lotus 1-2-3 model was developed to implement the results of the study. The user inputs the existing and proposed geometrics for a highway section, the level of traffic, and an analysis period. The model provides an estimate of the accident savings that can be expected and the present value of the accident cost reduction over time. An example output is shown in Figure 4. The model is in an early stage of development and refinements are anticipated. Once complete, it is intended to provide information to make more informed decisions concerning the benefits of improved highway geometrics.

Speed and Operating Cost Estimation

The Wisconsin Department of Transportation has made extensive use of the Highway Investment Analysis Package (HIAP). HIAP is the capacity-based procedure developed by the Federal Highway Administration in order to allow the user effects of highway improvements to be evaluated.

Experience with HIAP indicated that there were a number of shortcomings in the program. In particular, the program used outdated speed and capacity relationships and outdated operating cost data that was insensitive to highway geometry. It also provided inadequate evaluation of peak period conditions by understating peak traffic volumes.

Revisions to HIAP were made through a contract with the University of Wisconsin at Madison. Program modifications have been summarized in a paper by W.D. Berg and J. Choi, *Revision of the Highway Investment Analysis Package Methodology for Estimating Road-User Costs*. This paper was published by the Transportation Research Board in *Transportation Research Record 1156*.

The version of HIAP now in place has the following improvements:

1. Speed and capacity relationships based on the 1985 Capacity Manual,
2. Revised operating costs,
3. Direct input of grades and horizontal curves into operating cost estimates, and
4. Accurate simulation of peak traffic flows.

Experience, with the new program is limited. However, case study work indicates that the model now captures operating cost benefits that are obtained through improved geometrics. These benefits can be critical in the evaluation of reconstruction projects and were previously unavailable because of the insensitivity of the model.

Future Direction for Research

Wisconsin recently implemented a process to gather detailed geometric information at 1/100 of a mile increments on our state truck highway system. This information is obtained automatically through the use of a specially outfitted van. Initially, software was developed to produce an accurate representation of the vertical and horizontal profile of a highway section. This research is now being extended through a contract with the University of Wisconsin at Madison. The goals of the research are as follows:

1. Provide an automatic system to flag highway deficiencies for further analysis;
2. Provide a system to develop automobile and truck speed profiles for highway segments. This information is useful for design and safety evaluation; and
3. Provide a highly refined system to estimate speed and operating cost benefits associated with improved highway geometrics. This result will supplement and extend the research undertaken to modify HIAP.

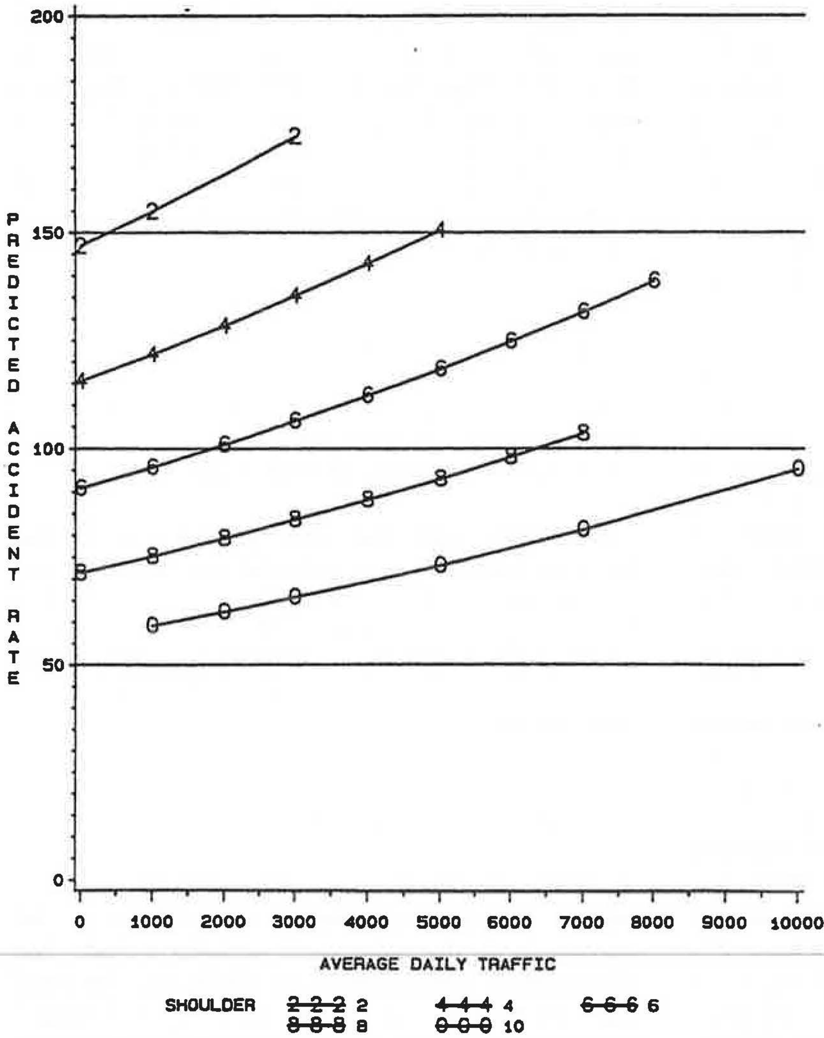

FIGURE 2 Mobility accidents per 100 million VMT (passing = 60 percent, pavement = 22).

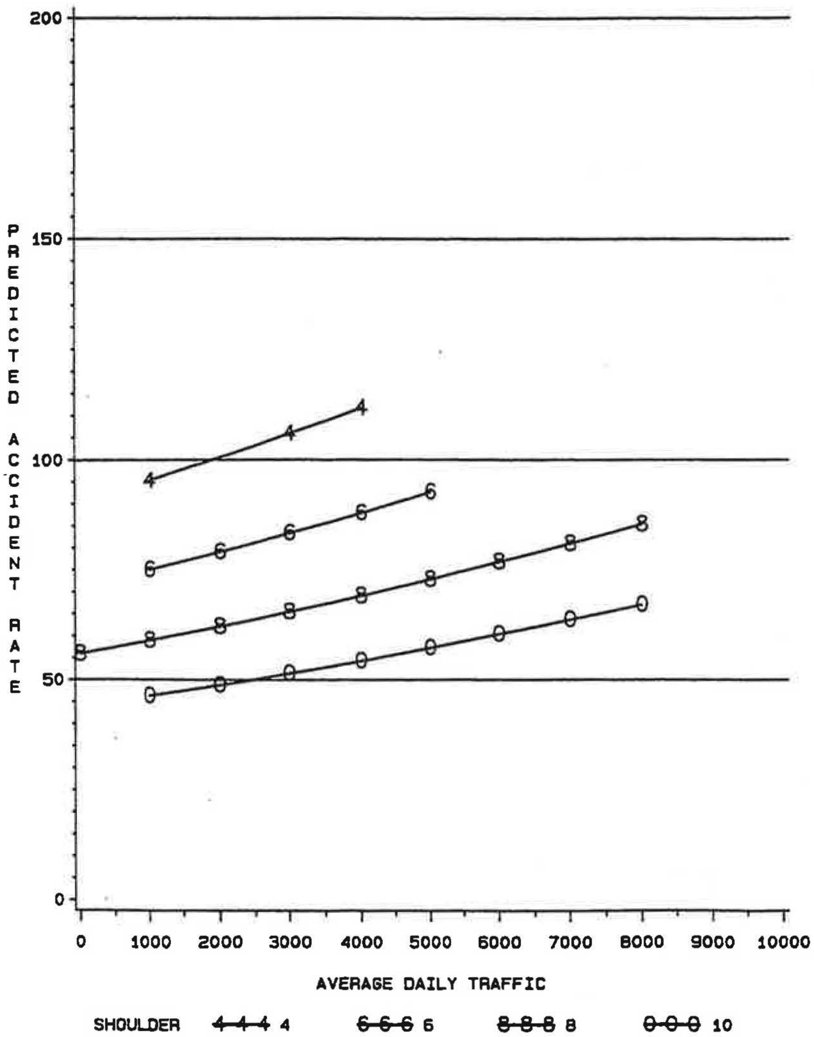

FIGURE 3 Mobility accidents per 100 million VMT (passing = 60 percent, pavement = 24).

TWO-LANE RURAL STH MOBILITY
ACCIDENT REDUCTION WORKSHEET

WisDOT Economic Policy and
Analysis Section

1. GEOMETRIC CHANGES

Type in a project description here.

Geometrics:	Pavement	Shoulder	Passing
Highway design type A.	22	3	40
Highway design type B.	24	6	60

2. TRAFFIC

Completion year average daily traffic (ADT) is:	1220
Ten years after completion ADT will be:	1440
Twenty years after completion ADT will be:	1660

3. ANALYSIS PERIOD

First Year of Analysis Period:	1991
Length of Analysis Period (Years):	40
Project Completion Year:	1991

4. DISCOUNT RATE

The discount rate is 5 percent.

(WisDOT's standard discount rate is 5%.)

5. CONCLUSIONS

Changing a highway from type A to type B will result in the following:

	Accident Rate	Annual Accidents Per Mile	Annual Acc. cost Per Mile
Highway design type A.	161	0.72	$5,970
Highway design type B.	76	0.34	$2,802
Accident reductions:		0.38	$3,168

Changing a highway from type A to type B in 1991
will result in accident reductions worth $55,052
over a 40 year period in 1991
for each mile of highway.

FIGURE 4.

Summary

The Wisconsin Department of Transportation is committed to wise investment principles. Responsible management must ensure that the benefits of transportation investments are greater than the costs. Economic evaluations provide essential management information, and efforts to develop, refine, and implement practical economic analysis tools must continue.

APPENDICES

Appendix A
Beyond the Green Book

Final Program

Monday, November 9, 1987

Bonnell Room, 4th Floor

8:00 a.m.	Registration

Salon F

9:00 a.m.	Introduction and Welcome, Jerome W. Hall, University of New Mexico
9:15 a.m.	Conference Overview, Ronald C. Pfefer, Traffic Institute, Northwestern University
9:30 a.m.	AASHTO Review of the Green Book, Frank D. Holzmann, AASHTO Task Force on Geometric Design, Texas Department of State Highways and Public Transportation
10:15 a.m.	Coffee Break
10:30 a.m.	Overviews of the Green Book, Joel Leisch, Jack E. Leisch and Associates, John C. Glennon, John C. Glennon, Chtd.
12:30 p.m.	Luncheon - Salon E Speaker: Raymond E. Stotzer, Engineer-Director Texas State Department of Highways and Public Transportation

Salon F

2:00 p.m.	Reflecting Operational Effects of Geometrics Throughout the Design Process, Douglas W. Harwood, Principal Traffic Engineer Midwest Research Institute
2:45: p.m.	Applying Human Factors Principles and Tools, Richard M. Michaels, Director, Urban Transportation Center, University of Illinois
3:15 p.m.	Coffee Break
3:30 p.m.	The Role of Computer Tools-Current and Potential CADD Systems, William J. Wiedelman, Mid States Engineering Simulation Models of Vehicle Dynamics, Raymond R. McHenry, McHenry Consultants, Inc. Expert Systems, Geoffrey D. Gosling, Institute of Transportation Systems University of California, Berkeley Economic Evaluation Models, Mark Wolfgram Wisconsin Department of Transportation

Tuesday, November 10, 1987

Salon F

8:00 a.m.	Current And Recent Research, George B.Pilkington, II, Federal Highway Administration
8:30 a.m.	Current Work on Speed Change Lanes, William R. Reilly, JHK & Associates
8:45 a.m.	Updates and Enhancements, John M. Mason, Jr., Pennsylvania State University
9:15 a.m.	Introduction to Workshops, R. Kenneth Shearin, Jr., Roy Jorgensen Associates, Inc.
9:45 a.m.	Coffee Break

10:00 a.m. *Workshop Sessions*: The workshops will provide the conference attendees an opportunity to discuss how the Green Book might be changed or supplemented. Workshop attendees will be invited to discuss their experience in using the Green Book and to present ideas for increasing its usefulness to the highway design community.

(Rooms to be Announced)

Tools and Techniques to Reflect Operational Effects in the Design Process: To identify tools and techniques to reflect the operational effects of geometrics.
Leaders: Daniel B. Fambro, Texas Transportation Institute, Timothy E. Neuman, Jack E. Leisch & Associates

Means for Incorporating Operational Effects: To identify how the design process and design guides may be modified to reflect the operational effects of geometric design.
Leaders: Jerome W. Hall, John M. Mason, Jr.

Opportunities for Updating and Enhancing the Green Book: To identify areas of the Green Book Where user experience suggests the need for supplemental information and clarification.
Leaders: Donald Diller, Wyoming Highway Department, Norman H. Roush, West Virginia Department of Highways

Geometric Design Research to Support Improvement of the Design Process: To discuss the implementation of research completed since publication of the Green Book and to develop a list of topics in order of priority for future research to support improvements in the Green Book. *Leaders*: Julie A. Cirillo, Federal Highway Administration, Robert P. Morris, Virginia Department of Transportation

12:00 p.m. Luncheon - Salon E

Salon F

1:30 p.m. Cadd Technology
Timothy E. Neuman

2:00 p.m. *Workshop Summaries*: The results of the workshop sessions will be reported back to the conference in this session and summarized for consideration by the AASHTO Task Force on Geometric Design and the appropriate TRB Committees.

4:00 p.m. Conference Wrap-up
Ronald C. Pfefer

4:15 p.m. Adjournment

Wednesday, November 11, 1987

8:30 a.m. Committee Meetings

Barton Room Committee on Operational Effects of Geometrics,
Jerome W. Hall, Chair

Bonnell Room Committee on Geometric Design, John C. Glennon, Chair

All conference attendees are invited to participate in the committee meetings.

12:00 p.m. Adjournment

Appendix B
A Critical Review of the Green Book—One Researcher's Perspective

By: John C. Glennon

Objective

To give perspective to the importance of the Green Book, its portrayal of current technology and what the needs are for future revisions.

Green Book Preparation

- Spare-time writing
- Loosely structured coordination
- Cursory editing
- Duplication of worn-out text structure
- No effort to improve some major sections

Green Book Impact

Major technical and economic effects on the Federal Highway Administration (FHWA), state, cities, counties, parishes, townships, U.S. Park Service, airports, sports complexes, and so forth. Inconceivable not to commit large developmental funds.

Rating of Green Book

Characteristic	Rating (1)
Comprehensiveness	8
Tie to other standards	7
Graphics	6
Language	5
Use of references	5
Use of optimization techniques	2
Use of current technology	5
Consideration of trade-offs	2
Integration with traffic control needs	2
Recognition of need for flexibility	2
Treatment of design consistency	2
Useability (organization, indexing, and cross-referencing)	2

Passing Sight Distance

Current model does not represent operational behavior. More appropriate model first discovered in 1969. Several prominent papers about flaws in AASHTO model over last 18 years. Lack of correspondence between the Green Book and the Manual on Uniform Traffic Control Devices (MUTCD). Model gives faulty conclusions about passing sight distance needs around large trucks.

Stopping Sight Distance

Sight distance requirements not tied to needs of site. Some inconsistencies for trucks and on highway curves.

Intersection Sight Distance

The Green Book does not recognize headlight height as critical dimension. Presents Case I sight distance, then admits it is unsafe. Case III-B sight distances are not practical.

Railroad Crossing Sight Distance

The Green Book sight triangles promote train-truck collisions because truck cannot stop from the sighting point. Even minimal indecision creates a dilemma.

Providing Sight Distance on Highway Curves

Although the Green Book mentions that inside offsets vary both by length of curve and position on curve it only presents middle ordinate values for long curves. Offset requirements could be presented either graphically or mathematically.

Flattening Existing Sharp Crests

The Green Book ignores profile characteristics of sight distance. Flattening sharp crests is expensive and can degrade safety.

Roadside Design

The Green Book seems disorganized. Slopes are discussed in one place, roadside barriers in another, and clear zones in yet another. It encourages use at 3:1 slopes, which not only conflicts with previous AASHTO policy, but also the definitive research shows 4:1 to be the most reasonable break point. The Green Book could be interpreted to allow 1.5 foot clear zones on rural arterials, and it often alludes to AASHTO Barrier Guide which is not a roadside design guide.

Green Book Needs

1. Develop more dynamic process to update policies in a more timely fashion.
2. Develop a definitive program to research and synthesize methodology to promote optimization, design consistency, operational effectiveness, and so forth.
3. Involve research community to identify, critique, and evaluate useful research for inclusion in the Green Book.
4. Develop policies that address the widest possible audience and promote a broader understanding of underlying principles.
5. Detailed treatment of safety and operational tradeoffs including the use of probability models, and so forth.
6. Comprehensive discussion of economic trade-offs.
7. Develop a clearer connection between design elements and traffic control devices.
8. Stress the maintenance of design factors, such as cross slope, superelevation, pavement skid resistance, sight obstruction clearance, and so forth.
9. Broaden discussion of which dimensions can be compromised and which cannot and how much under what conditions.
10. Develop a more realistic approach to litigation concerns.

Appendix C
Green Book Problems Cited by AASHTO Member Agencies

Sight-Distance (23 citations):
FHWA-TS-78-214, FHWA/RD-81/10, FHWA-IP-82-3, FHWA-TS-82-232, FHWA/RD-83/021, FHWA/RD-83/067, FHWA/RD-83/105, FHWA-TS-86-215, FHWA/RD-87/015, NCHRP R270, TRB SR214, Pending in NCHRP

Horizontal Curves (13 citations):
FHWA-RD-78-202, FHWA-TS-82-232, FHWA/RD-83/021, FHWA/RD-86/035, FHWA/RD-86/167, FHWA/RD-87/047, NCHRP 184, TRB SR211, TRB SR214, FHWA HC Rehabilitation study (under way)

Design Vehicles (12 citations):
FHWA-TS-82-233, FHWA/RD-87/047, TRB SR211, NCHRP P2-16

Capacity - HC (11 citations):
FHWA-RRR-1980, FHWA-IP-82-3

Clear Roadsides/Zones (10 citations):
FHWA-RD78-202, FHWA/RD-83/021, FHWA-TS-81-216, NCHRP R214, NCHRP R247, TRB SR211, TRB SR214

Vertical Curves (9 citations):
FHWA-TS-82-232, TRB SR214

Shoulders (8 citations):
FHWA-TS-81-216, FHWA-TS-82-232, FHWA/RD-83/021, FHWA/RD-85/028, FHWA/RD-87/047, NCHRP R197, NCHRP R254, NCHRP S63, TRB SR211, TRB SR214

Speed Change Lanes (4 citations):
FHWA/RD-81/10, FHWA/RD-81/103, FHWA-IP-82-3, FHWA-TS-82-232, FHWA/RD-86/167, NCHRP P2-16, NCHRP P3-35, NCHRP R279, TRB SR211, NCHRP P2-16, NCHRP P3-35.

Intersections (4 citations):
FHWA/RD-81/10, FHWA/RD-81/103, FHWA/RD-83/021, FHWA-IP-82-3, FHWA-TS-82-232, FHWA/RD-86/167, FHWA/RD-87/015, FHWA/RD-87/047, NCHRP R219, NCHRP R270, NCHRP R279, TRB SR214, TRB SR211, NCHRP P2-16 NCHRP P17-7

Medians (4 citations):
NCHRP R279, NCHRP R282

Ramp Spacing (4 citations)

Climbing Lanes (3 citations):
FHWA/RD-86/167, NCHRP R279, TRB SR211

Curbs (3 citations):
FHWA/RD-86/013, NCHRP R279

Design Speed (3 citations):
FHWA-TS-78-214, FHWA/RD-83/021, FHWA/RD-86/167, FHWA-TS-86-215, TRB SR211, TRB SR214, NCHRP P2-16

Interstate Standards (3 citations):
FHWA/RD-81/103, FHWA-TS-82-232, FHWA/RD-83/105, FHWA/RD-86/167, TRB SR211

Pavement Width (3 citations):
FHWA-RRR-1980, FHWA/RD-81/10, FHWA/RD-81/103, FHWA-TS-81-216, FHWA-IP-82-3, FHWA-TS-82-232, FHWA/RD-83/021, FHWA/RD-86/167, NCHRP R197, NCHRP R214, NCHRP R282, TRB SR214, TRB SR211, NCHRP P2-16, NCHRP P15-12

Rehabilitation - 3R/4R (3 citations):
FHWA-RD-78-202, FHWA-TS-78-214, FHWA-RRR-1980, FHWA/RD-81/10, FHWA/RD-81/103, FHWA-TS-81-216, FHWA-IP-82-3, FHWA-TS-82-232, FHWA/RD-83/021, FHWA/RD-83/105, FHWA/RD-85/028, FHWA/RD-86/167, FHWA-TS-86-215, FHWA/RD-87/015, FHWA/RD-87/047, NCHRP R197, NCHRP R214, NCHRP R247, NCHRP R254, NCHRP R270, NCHRP R279, TRB SR214, TRB SR211, FHWA HC Rehabilitation study (under way), NCHRP P15-12

Delineation (2 citations):
FHWA-TS-81-216, FHWA/RD-83/105, NCHRP R214

Lane Balance (2 citations):
NCHRP R282, TRB SR211

Auxiliary Lanes (1 citation):
FHWA-1P-82-3, FHWA/RD-86/167, TRB SR211

Grades (1 citation):
FHWA-RD-78-202, FHWA-TS-82-232, FHWA/RD-83/021, FHWA/RD-86/167, NCHRP R185, NCHRP R214, NCHRP R270, TRB SR211

Level of Safety (1 citation):
NCHRP P3-33

MUTCD Conflicts (1 citation)

Noise Abatement (1 citation):
NCHRP S87, NCHRP P25-2

Pedestrians (1 citation):
FHWA/RD-83/105, FHWA-IP-82-3, NCHRP R261, NCHRP R262, NCHRP R270, NCHRP R279

Railroad Crossings (1 citation):
FHWA-TS-78-214, FHWA/RD-83/105, FHWA-TS-82-233, FHWA-TS-86-215, NCHRP R270, NCHRP R288, TRB SR211, NCHRP P2-16

Rural/Urban Differences (1 citation):
FHWA/RD-83/021, NCHRP R282, NCHRP P3-33

Slopes (1 citation):
FHWA-TS-81-216, FHWA-TS-82-232, FHWA/RD-84/006, FHWA/RD-87/047, NCHRP R214, NCHRP R247, NCHRP R254, TRB SR214

Three-Lane Sections (1 citation):
FHWA/RD-85/028

Truck Pullovers (1 citation):
FHWA/RD-86/167, NCHRP R279, TRB SR211, NCHRP P2-16

Two-Way Left-Turn Lanes (1 citation):
FHWA-IP-82-3, FHWA/RD-85/028, NCHRP R279, NCHRP R282, NCHRP P2-16

Urban Intersections (1 citation):
FHWA-IP-82-3, FHWA-TS-82-232, FHWA/RD-86/167, FHWA/RD-87/015, NCHRP R219, NCHRP R270, NCHRP R279, NCHRP R282, NCHRP P2-16, NCHRP P3-33, NCHRP P17-7

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Appendix E
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Leader: Jerome Hall

Session 3, Group 3A

Leader: Norman Roush

Group 3B

Leader: Donald Diller

Session 4, Group 4A

Leader: Michael Freitas

Group 4B

Leader: Robert Morris

Appendix F
Conference Joint Planning Committee

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Angelia V. Arrington,
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Appendix G
Workshop Resource Materials

Before the conference, detailed workshop resource materials were prepared to guide the discussion. This Appendix presents the materials for the workshop. These were provided to each session leader in advance of the conference, and they were made available to each workshop participant on day 1 of the conference. The workshops were held on day 2.

The workshop resource materials for each workshop followed the same basic structure:

1. A summary introduced the reader to the purpose of the workshop.
2. Abstracts presented the pertinent details of the specific topics under discussion.
3. An evaluation form allowed each workshop participant to present his or her views on each topic.