NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM REPORT **159**

WEAVING AREAS

DESIGN AND ANALYSIS

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WEAVING AREAS
DESIGN AND ANALYSIS

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RESEARCH SPONSORED BY THE AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS IN COOPERATION WITH THE FEDERAL HIGHWAY ADMINISTRATION

AREAS OF INTEREST:
- HIGHWAY DESIGN
- TRAFFIC CONTROL AND OPERATIONS
- TRAFFIC MEASUREMENTS

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C. 1975

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to its parent organization, the National Academy of Sciences, a private, nonprofit institution, is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the Academy and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are responsibilities of the Academy and its Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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FOREWORD

By Staff

Transportation Research Board

Highway designers, traffic planning analysts, and traffic engineers concerned with freeway traffic operations will be interested in the research findings provided by this report. The study investigations, carried out over a four-year period, have led to the development of new procedures for analyzing and designing weaving sections by means of analytic manipulations, nomograph solutions, or application of a computer program. These procedures, including complete program documentation and sample problems, are presented in Appendices E and F of the report. Other parts of the report present evaluations of the methodology offered in Chapters 7 and 8 of the *Highway Capacity Manual* and describe the research that led to the development of the recommended procedures.

This study was initiated because of the belief that existing design criteria for weaving sections needed to be revised in order to take into account additional variables, such as geometrics, traffic composition, and proportion of weaving vehicles. The project was structured in two parts. The first phase had as its objective evaluation of existing techniques using an existing data base compiled and provided by the Federal Highway Administration, and development of an appropriate follow-up research program. The second phase included collection of new data on weaving area operations, further use of the existing data base, and developmental research leading to the recommended procedures.

Both phases of the project were conducted by the Polytechnic Institute of New York, and this report combines the findings and conclusions from the entire study. Because of their voluminousness, seven of the appendices that formed part of the final report are not being published. They describe the various data bases, data collection techniques, and detailed analyses of the *Highway Capacity Manual* procedures. However, these materials are available on a loan basis to interested researchers by request to the NCHRP Program Director.

CONTENTS

ACKNOWLEDGMENTS

The research reported herein was performed under NCHRP Project 3-15 by the Department of Transportation Planning and Engineering, Polytechnic Institute of New York. Principal investigator for the project was Louis J. Pignataro, Head of Department and Professor of Transportation Engineering. He was joined in the research and the writing of the report by William R. McShane, Associate Professor; Roger P. Roess, Assistant Professor; Bumjung Lee, Assistant Professor; and Kenneth W. Crowley, Associate Professor.

The researchers are indebted to the agencies and individuals who aided them in collecting supplemental data, in identifying and selecting sites, and in several other tasks essential to the research. They offer special thanks to the Federal Highway Administration, which provided its 1963 Urban Weaving Area Capacity Study data base and other data.

The researchers are particularly grateful to Jack E. Leisch, who acted as a consultant and advisor to them throughout the research. The assistance of E. Leiberman early in the project in adapting the ITTE capacity programs is likewise greatly appreciated.

The aid and support of other Polytechnic staff members is also gratefully acknowledged: J. J. Starace, for data collection and equipment maintenance; T. W. Casey, for data processing and analysis; M. M. Nelson, for computational work; and R. Pollack, for contributions to Appendix H.

WEAVING AREAS
DESIGN AND ANALYSIS

SUMMARY Over twenty years have passed since the original *Highway Capacity Manual* (HCM) first appeared in print. In the interim the procedures then developed, as well as the modifications, extensions, and new methodologies presented in the 1965 edition of the HCM, have become national guides for the design and analysis of highway sections. Their constant application has exposed them to detailed scrutiny by traffic planning, design, and operations specialists. Exhaustive "on-the-job" evaluation has exposed such problem areas as instructions that may be subject to misinterpretation, procedures that are complex and difficult to apply, and results that sometimes appear unreasonable.

The research was divided into two major undertakings: (1) evaluation of the HCM procedures for weaving area design/analysis and (2) development of a new procedure. In the first undertaking, the approach employed three prime elements. They were (1) the analysis of the mechanisms and internal structure of the three applicable HCM procedures, (2) an evaluation of the accuracy of each procedure using both peak-hour and 6-min data available in 1969, and (3) an analysis of the consistency of the three procedures in predicting performance. The available data were from the 1963 BPR Urban Weaving Area Capacity Study, which was not used in the 1965 HCM procedure development.

The analysis of mechanisms and internal structure indicated procedural flaws in the HCM Chapter 7, "Weaving." These included (1) difficulties and lack of clarity in the use and/or interaction of quality of flow and level of service; (2) the k-factors used for expansion of the minor weaving flow have neither the 1.0 to 3.0 range nor the systematic relation to weaving volume and length implied in the HCM; (3) geometric considerations per se are not integral to the procedure, despite evidence in the available data of its importance; (4) HCM Table 7.1—itself a compensating device—is apparently not stated as the procedure writers intended.

There are two prime areas of accuracy analysis: (1) level-of-service accuracy of the three HCM procedures (one in HCM Chapter 7 and two in HCM Chapter 8), and (2) lane 1 volume prediction accuracy and other elements related to the Chapter 8 procedures.

The following conclusions may be drawn on the first point:

1. The accuracy of level-of-service predictions by HCM Chapter 7 is highest for basic weaving sections, followed by auxiliary lane cases and major weaves.* Accuracy of the procedure is generally poor. Although space mean speed was used in level-of-service determination, the use of operating speed would have further degraded the accuracy;

2. The HCM recommends use of its Chapter 8 for auxiliary lane cases, although Chapter 7 produces more accurate estimates of level of service; and

3. Level-of-service predictions for auxiliary lane cases by HCM Chapter 8 tend to be better than actual field conditions.

* A major weave is defind as a weaving section with two or more lanes on each of three or more legs.

The accuracy of HCM Chapter 8 regarding auxiliary lane cases was further investigated. The two procedures of this chapter depend on the prediction of lane 1 volumes in advance of ramps. Although HCM recommends the first procedure for cases of levels of service A, B, and C and the second for level D (commonly used for E also), it was found that the first yields more accurate prediction across *all* levels of service. The accuracy of HCM Figure 8.22, which predicts the percentage of trucks in lane 1, was also tested. Although the differences noted for four- and six-lane freeways are not as drastic as for eight-lane freeways, the figure does not appear to accurately represent the relationship between freeway volume and the percentage of trucks in lane 1.

The consistency of the three procedures in specifying level of service was examined by both data and a range of constructed cases. The results indicate that HCM Chapter 7 yields level-of-service estimates poorer than Chapter 8 for relatively short or wide sections and better levels of service than Chapter 8 for longer, narrower sections.

Based on the results of the analyses cited, a study program directed toward the development of a new weaving design/analysis procedure, including a substantial supplemental data collection effort, was recommended to NCHRP. The program also included as an objective the better understanding of the mechanisms of weaving. The implementation of this program constitutes the second major undertaking.

From the beginning, it was intended that the procedures would evolve from an interactive evaluation of macroscopic and microscopic data. The microscopic analysis—lane changing, concentrations within sections, extent of segregation, some analytic modeling—is important in understanding basic mechanisms and in guiding the macroscopic development. The macroscopic data, on the other hand, allow for a calibration using a range of facilities and conditions at acceptable cost and effort. The calibration was done by regression analyses on models developed consistent with the microscopic results. The resultant procedure was checked on cases withheld from the data base for that purpose.

The procedure developed from this research and recommended for use is presented as a self-contained document in Appendix E of this report, for easy use. It was circulated to five states as a pre-test (not necessarily endorsement) on its clarity and ease of uses. Three responses were received. The procedure allows for both analytic and nomographic solutions and should be used in lieu of the procedure of HCM Chapters 7 and 8 for auxiliary lane and major weave cases.

The computer program detailed in Appendix F is recommended as a computational aid, particularly in analysis problems.

For multiple weaves, the procedure developed herein is also recommended. It should be applied subject to the guidelines and cautions stated in Chapter Two and also in Appendix I.

This report also contains information on a survey of current practices of weaving section design/analysis, a methodology to decide priorities for data supplements of ramp cases, experiences with photographic data collection and reduction, and other insights acquired in the course of the research. The exposition on basic mechanisms follows the points already cited—lane changing, concentrations within sections, extent of presegregation, and some analytic modeling.

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

Over twenty years have passed since the original *Highway Capacity Manual* (HCM) (*1*) first appeared in print. In the interim the procedures then developed, as well as the modifications, extensions, and new methodologies presented in the 1965 edition of the manual (*2*), have become national guides for the design and analysis of highway sections. As such they have been exposed, through constant application, to detailed scrutiny by traffic planning, design, and operations specialists. Exhaustive "on-the-job" evaluation has exposed such problem areas as instructions that may be subject to misinterpretation, procedures that are complex and difficult to apply, and results that sometimes appear unreasonable.

In recent years, because urban freeway design and analysis has been an area of much interest, that segment of the manual dealing with problems of weaving and ramps has had particularly heavy use. This has resulted in its being the specific target of many of the comments and criticisms.

SCOPE AND MISSION

In 1969, NCHRP authorized Project 3-15. The project statement specified that "design criteria for weaving sections on multilane controlled-access highways require revision and updating, taking into account such variables as roadway geometrics, composition of traffic, volumes of main-line vehicles, and volumes of weaving vehicles." The three main objectives of this study were specified as:

1. Analyze and evaluate the procedures recommended in Chapters 7 and 8 of the 1965 HCM by using presently available (i.e., 1969) field data.
2. Based on the findings of the first objective, develop a study program that will lead to improved techniques for the analysis and design of weaving sections.
3. Within the constraints of time and funds, a limited data collection and analysis program may be undertaken toward the accomplishments of the second objective.

This report is the culmination of the defined mission and includes the definition and execution of the study program cited in the second item. The study program recommended:

1. The collection of a supplemental data base to augment the then-available data, and to fill gaps in the existing data. Principal data needs were for levels of service B and C and for data at all levels of service on weaving sections of 1,500-ft length and longer;
2. Development of a new or revised weaving area design/analysis procedure using the upgraded or composite data base;
3. The extensive investigation of underlying mechanisms and relationships among parameters in weaving sections.

The study program was executed in a continuation of the research beyond the original three objectives.

HISTORICAL CONTEXT

The original HCM was published in 1950. It was meant to be a practical guide to the design and evaluation of streets and highways in terms of their traffic-carrying capability. A major purpose of the manual was to ensure consistency of procedures in the national program of highway design and construction. The manual's procedures were largely based on, and calibrated with, data collected before 1948. In many instances the available data base was quite sparse. Thus, it could not be expected to serve adequately in the design of freeway systems with their complexities of, among other things, weaving sections and multiple on- and off-ramp situations. The fact that the 1950 HCM worked as well as it did says much for the engineering judgment of the members of the Highway Capacity Committee who developed it.

In 1953, the Highway Capacity Committee was reactivated to continue its study of highway capacity and ultimately to prepare a new manual. The study was accomplished with the aid of a team from the U.S. Bureau of Public Roads (BRP). The new HCM was published in 1965. It, like its predecessor, was to be a practical guide in capacity analysis for design and evaluation. Reflecting the changed needs of the practicing engineer, this new manual devoted a significant amount of attention to freeway design, and such components as weaving and ramps had significantly expanded chapters devoted to them. As before, the procedures developed were, insofar as possible, based on the analysis of data collected by a variety of governmental units in a number of states and over a span of years. Where data were incomplete, it frequently became necessary for members of the committee to apply their collective engineering judgment toward the development and explanation of rational procedures. It might have been more desirable to delay publication of a new manual until a complete data base was available, but this was not considered possible. The 1950 manual was out of date and engineers throughout the country were regularly making major "adjustments" to the procedures in developing their designs. This was considered to be unacceptable. It was believed that it was better to have a new manual that would again ensure consistent design procedures—even though there were reservations concerning some procedures—than to have no manual at all. In such a light was the 1965 edition published.

It is not surprising then that a few years heavy use of the manual and its intense scrutiny in the field have given rise to the need—as evidenced by this project—for analysis and evaluation of certain recommended procedures.

RESEARCH APPROACH

The research was divided into two major undertakings: (1) evaluation of the HCM procedures for weaving area design/analysis, and (2) development of a new procedure. The second undertaking was defined by the results of the first.

The approach employed in the first undertaking had three prime elements: (1) analysis of the mechanisms and internal structure of the three applicable HCM procedures, (2) evaluation of the accuracy of each procedure using both peak-hour and 6-min data available in 1969, and (3) analysis of the consistency of the three procedures in predicting performance. The available data were also used for such elements of structural evaluation as *k*-factors, quality of flow, lane 1 volumes, and truck presence in lane 1. A limited amount of new data was collected.

The approach employed in the second undertaking centered on the development of a new weaving procedure properly calibrated and on a better understanding of the mechanisms of weaving. A rather extensive data base was collected by time-lapse photography. From the beginning it was intended that the procedure would evolve from an interactive evaluation of macroscopic and microscopic data. The microscopic analysis—lane changing, concentrations within sections, extent of segregation, some analytic modeling—is important in understanding basic mechanisms and in guiding the macroscopic development. The macroscopic data, on the other hand, allow for a calibration using a range of facilities and conditions at acceptable cost and effort. The calibration was done by regression analysis on models developed consistent with the microscopic results. The resultant procedure was checked on cases withheld from the data base for that purpose; it was also subjected to a pre-test to aid in determining clarity and ease of use by personnel in departments of transportation or public works of three states.

The end result of research under NCHRP auspices should be a product of direct use to the practicing engineer. It must therefore be part of the research approach to provide this product. To this end, the final recommended procedure is written as a self-contained document and is contained herein as Appendix E. A computer program implementing it is described in Appendix F.

As part of the research, one multiple weave site was filmed. On the basis of this and other data, guidelines for application of the recommended procedure to multiple weaves were generated.

DATA AVAILABLE

It should be noted that the original data base used in developing the weaving procedure of HCM Chapter 7 was not extant at the time of the present study. Much of this data base would have dated to the original weaving design curves of the 1950 HCM and the modifications reported (*3*). As a consequence, it was not possible to exhibit the distribution of data, nor to compute the confidence bounds on the existing curves, nor to estimate the merit of increasing the size of the data base. However, the levels A, B, and C procedures of HCM Chapter 8 made such analyses possible. Aspects of these procedures are discussed in Appendix XV,* including the statistical distinction of the cases of that procedure.

Two data bases were available. One data base was comprised of the data from the 1963 BPR Urban Weaving Area Capacity Study and the other of the data collected for the study program implemented in this research. These bases are referred to as the BPR and project data bases, respectively, and are described briefly. Details are given in Appendices I and II.*

BPR Data Base

At about the time drafts of chapters for the 1965 HCM were being developed, a nationwide program of data collection was being undertaken by the BPR. The Urban Weaving Area Capacity Study involved collection of weaving movements by type for periods of 1 to 2 hr in 6-min intervals at a number of locations in the East, Midwest, and Far West. Samples of weaving and through-vehicle speeds were collected at the same time. The sites studied represented simple and multiple weave areas, one- and two-sided weaving, simple and compound weaving. In addition, a number of the locations could be considered as ramp configurations. Although Appendix B of the 1965 HCM contains selected observations from these studies, the data were not used in developing the procedures of Chapters 7 and 8.

Most of the data base utilized in the regression analyses of the levels-of-service A, B, and C procedures of HCM Chapter 8 was also available.

The 1963 BPR package provided to the researchers consisted of a total of fifty-eight experiments conducted at forty different locations. Of these, forty-one experiments collected information about various forms of simple weaving sections (i.e., two entrance and two exit legs). The remaining seventeen experiments were of multiple weave configurations (i.e., more than two entrance legs and/or more than two exit legs). The BPR also provided data for an additional seven experiments—all simple weaves—conducted at four locations around Washington, D.C. These latter data sets were pilot studies conducted to develop the procedures that were subsequently used in the 1963 Urban Weaving Area Capacity Study.

One simple weave experiment could not be used because of highly questionable volume counts. Five of the seven pilot study experiments were added to the original data giving a total of forty-five different experiments at thirty-four different locations in the U.S. Eighteen experiments were conducted in the AM peak and twenty-seven in the PM peak. Of the seventeen multiple weave cases available, only four were "clean" cases (i.e., without additional complicating factors). Incomplete specification of data, segments of

* Not included in this publication. See Appendix J herein for additional information.

complicated geometry, and other problems prevented use of thirteen experiments and allowed only limited use of the other four.

Project Data Base

Data were collected in the Northeast U.S. at seventeen sites, one of which included a multiple weave section. Guidelines that governed site selection and data collection specified (1) both major weaves and auxiliary lane cases were to be collected, (2) all levels of service were to be observed, and (3) a range of lengths was to be so selected as to complement the BPR data base, if possible.

Time-lapse ground-based photography was selected as the mode of data collection because (1) it avoided the necessity for large field crews, (2) it was the only feasible way to provide some microscopic data concerning internal movements in weaving sections, and (3) aerial photography was too costly. All photography was shot in color at two frames per second in which a digital timer was in view via a split-image lens.

The sections were filmed with one camera, sometimes two—the fields of the two cameras did not overlap in those cases.

Data were reduced by trace or by input/output match of every vehicle for all but two experiments. For the five experiments (including the multiple weave) on which vehicle traces were possible,* lane changes were recorded by subsection and lane of occurrence for each vehicle.

RELEVANT LITERATURE

At the beginning of the research the literature was surveyed for all articles and papers concerning weaving and/or ramp operations. The Highway Research Information Service (HRIS) was used, as well as independent reviews of major publication sources, including HRB special reports and records, NCHRP reports, *Traffic Engineering,* and *Traffic Engineering and Control.*

Articles treating both macroscopic and microscopic aspects of weaving, merging, and diverging traffic movements were inspected. A wide range of those having some applicability and relevance to the present research are detailed in the annotated bibliography of Appendix A. The most relevant of these is also addressed in Chapter Two.

DEFINITIONS AND TERMINOLOGY

Definitions and terminology used throughout this report are discussed in this section.

A weaving area's components (i.e., legs and movements) are identified and shown in Figure 1. Other weaving area terminology requiring definition includes:

- balanced—a section is said to be balanced when the same level of service is delivered to both nonweaving and weaving traffic.
- BPR—Bureau of Public Roads.
- configuration constrained—a situation in which a lane arrangement limits the weaving width W that can be delivered.
- FHWA—Federal Highway Administration (formerly BPR).
- HCM—the *Highway Capacity Manual* (1965 edition unless otherwise specified).
- leg—an input or output roadway.
- major weave—a weaving section in which three or more legs each have two or more lanes; see Figure 2 (B), (C), and (D).
- pcphpl—abbreviation for passenger car per hour per lane, the unit in which service volumes are expressed.
- PHF—peak-hour factor, the hourly volume divided by

* Wherever only one camera was used.

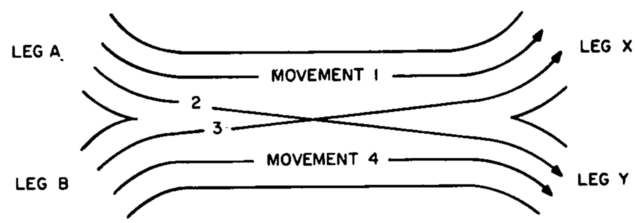

Figure 1. Diagram of legs and traffic flow movements for a weaving area.

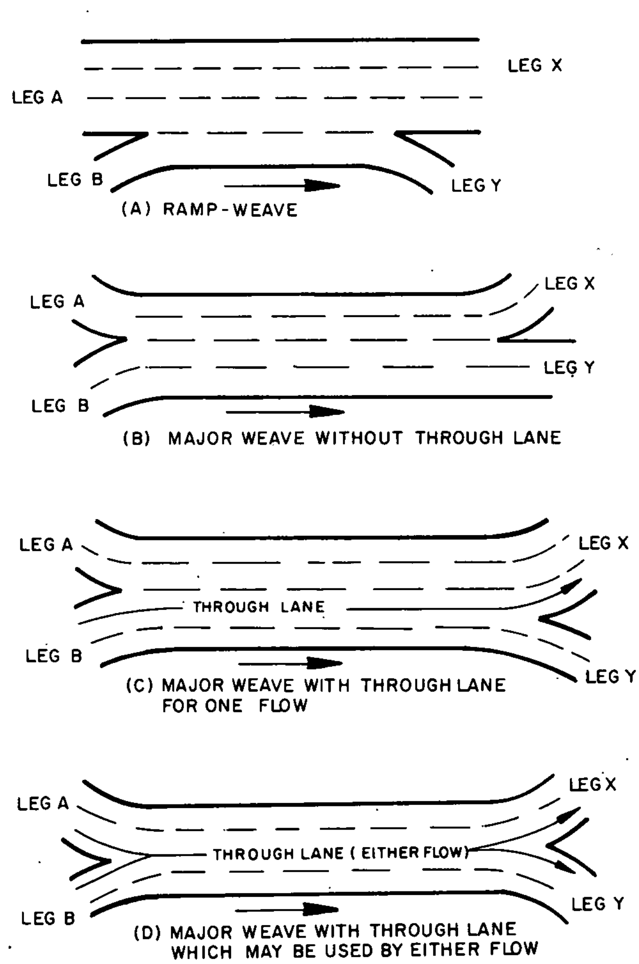

Figure 2. Diagrams of various configurations of weaving areas.

the hourly rate during the peak 5 min of that hour; this is as defined in the *Highway Capacity Manual.*

• ramp weave—a highway mainline with an on-ramp, off-ramp sequence (both single lanes) connected by an auxiliary lane; see Figure 2(A).

• SMS—space mean speed (mph).

• through lane—a lane on which at least one of two weaving flows (see Fig. 2(C) or (D), legs A-Y or B-X) can achieve its "weave" without a lane change; a lane may be a through lane for either or both weaving flows; when it is so for only one flow, it should be aligned with the greater flow in order that the benefit of a through lane can be realized.

Nomenclature requiring definition includes the variables:

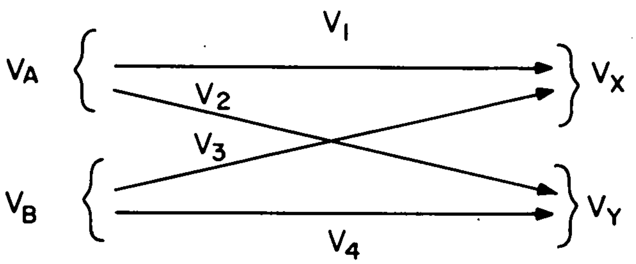

Figure 3. Diagram of volume parameters for a weaving area.

V_w = total weaving volume, in passenger cars per hour (pcph)
V_{wc} = total weaving volume (HCM notation), in pcph
V_{w2} = smaller weaving volume, in pcph
V_{nw} = total nonweaving volume, in pcph
V_{TOT} = total volume, in pcph
V = total volume (HCM notation), in pcph
SV = service volume, in pcph or pcph per lane (pcphpl)
S_w = speed of weaving volumes, in mph
S_{nw} = speed of nonweaving volumes, in mph
$\Delta S = (S_{nw} - S_w)$ = difference in speeds, in mph
L = section length, in hundreds of feet *
N = section width, in total lanes
W = width for weaving, in lanes *
N_{nw} = width for nonweaving, in lanes *
$VR = V_w/V_{TOT}$ = ratio of weaving to total volumes
R = ratio of smaller weaving to total weaving volume

Additional volume parameters are shown in Figure 3. Some volumes—particularly V_{w2} and V as used in the HCM—will generally be measured in vehicles per hour (vph); likewise, SV may be specified in pcph or in per lane values and may be corrected for standard adjustments when volumes are in vph. The proper course will be apparent in any given case by the context.

Other terminology and practices not specifically defined herein are consistent with the HCM.

* These may be fractional numbers.

CHAPTER TWO

FINDINGS

This chapter presents the prime findings and results of the research project. The first four sections relate to the first objective of the research—the evaluation of the existing HCM procedures related to weaving. They discuss internal structure of procedures and give an analysis of their accuracy and consistency in specifying levels of service as well as current practices. The findings are discussed in the sections "Development of a Weaving Procedure," "Mechnisms of Weaving: Results," and "Mechanisms of Weaving: Analysis." The need to develop a new procedure was based on the assessment of the HCM procedures.

The procedures of the HCM that relate to weaving are defined as:

1. Procedure 1 is the procedure defined in HCM Chapter 7, "Weaving."
2. Procedure 2 is the regression-based procedure defined in the first part of HCM Chapter 8, "Ramps."
3. Procedure 3 is the vehicle-distribution-profile procedure defined in the latter part of HCM Chapter 8, "Ramps."

The HCM recommends procedure 2 for ramp cases at levels of service A, B, and C and procedure 3 for ramp cases at level of service D. While not specifically recommended, procedure 3 is often applied to level of service E cases.

It should be noted that ramp-oriented procedures 2 and 3 were used only for auxiliary lane cases not only because of the limitations of the BPR data base but also because of the concurrence of the research agency and the advisory panel that on-ramp, off-ramp pairs without auxiliary lanes are characterized to a greater degree by merge and diverge (i.e., individual ramp) problems than by weaving. Accordingly, single-lane ramp sequences without auxiliary lanes were not collected in the project data base.

The thrust of the first-phase research was the analysis of simple weaves for which 908 6-min samples were available along with 11,000 travel-time measures. These were formatted for computer manipulation and punched on cards.

Two computer programs were already in existence at the initiation of the project that were of considerable use. They are the weaving and ramp capacity programs developed at the Institute of Transportation and Traffic Engineering (*4*, *5*). Before being put into use, the programs were carefully reviewed and, where applicable, modified and extended to provide additional power in analysis. Some of these modifications and extensions in the weaving capacity program included (1) an option of using either the services volumes contained in Tables 9.1 and 10.1 of the HCM or a set of exogeneously entered values, (2) the use of Table 7.1 of the HCM was altered, and (3) a test of "out-of-the-realm-of-weaving" was added. The use of truck equivalency factors on ramp grades was incorporated into the ramp capacity program. The modifications are described in further detail in Appendix XIV.*

INTERNAL STRUCTURE OF PROCEDURE 1

A number of analyses were undertaken to determine the viability and rationality of procedure 1. These analyses included an examination of the specified service criteria for clarity, internal consistency, and an examination of the development of the weaving chart with consideration of a recalibration thereof. The principal results of these analyses were as follows:

- Adequate description of the operating characteristics of a weaving section requires the specification of both a level of service and a quality of flow.
- The relationships between speed and level of service and quality of flow are not clearly specified by HCM, leading to confusion in interpretation.
- Quality of flow and level of service are not functionally dependent upon each other. The consistent relationship suggested by HCM Table 7.3 does not exist.
- Separate level-of-service standards for weaving and nonweaving vehicles would seem to produce a more accurate description of weaving section service characteristics.
- It appears that geometric configuration is a vital design factor.
- The development of the weaving chart was based on only sparse data. The k-values utilized as expansion factors were rationalized and not supported by data.
- The range of k-values exceeds the HCM specification of 1.0 to 3.0.
- The k-values do not relate to total weaving volume V_{we} (pcph) and section length L as depicted in the weaving chart. Constant k-curves do not exist as suggested in HCM.
- Should a valid expansion exist, it appears to involve several parameters and be more complex than that used in the HCM, in which only the minor weaving volume V_{w2} is expanded.

A brief discussion of each of these conclusions follows. A more extensive discussion is contained in Appendix IV.* It also contains aspects of the comparative structure of all three HCM procedures.

* Not included in this publication. See Appendix J herein for additional information.

Description of Service Characteristics

Although it is not clearly stated, the use of the HCM procedure requires the specification of both a level of service and quality of flow. Consider the HCM equation for the width of a weaving section:

$$N = \frac{V + (k - 1)\, V_{w2}}{SV} \tag{1}$$

in which

N = number of lanes in section;
V = total volume in section;
k = expansion factor;
V_{w2} = minor weaving volume; and
SV = service volume.

The length of the weaving section and the k-value used in the width equation are determined by entering the weaving chart with a specified weaving volume (in pcph) and quality of flow. Service volume SV is selected from HCM Table 9.1 (for freeways) and is dependent upon a specified level of service.

Most properly, quality of flow relates to the speed of weaving vehicles alone. Level of service describes the speed of all vehicles combined. Neither of these can adequately describe the operating characteristics of a weaving area. As quality of flow relates only to weaving vehicles, it can not be used alone to describe a section containing both weaving and nonweaving vehicles. Level of service treats collectively two flows with often widely differing characteristics and effectively conceals such differences. Only when both are specified is a complete picture drawn. Even this, however, produces an awkward, indistinct description, as subsequently discussed.

Speed Criteria

There are several problem areas that create a degree of confusion in the speed-service relationships detailed in the HCM. The first of these involves the use of operating speed as a criterion. Strictly defined, operating speed is the maximum speed at which a car can travel under prevailing traffic and roadway conditions without at any time exceeding the design speed. This parameter is most properly measured using a test vehicle. For satisfactory samples, data generally must be taken by observing sample vehicles. From a sample speed distribution such items as 85th percentile speed, median speed, and space mean speed can be determined. None of these corresponds directly to operating speed, although they may be used to estimate it. Of greater importance is the fact that such sample data were used to calibrate HCM procedures and were also collected in the 1963 BPR study. It is of extreme importance that sample data be accurately segregated into specified, standard service categories. Some of the analyses reported herein required such stratification by service categories. For these analyses, space mean speed rather than operating speed was used.

The stated speed criteria are ambiguous to a large degree. The specifications of quality of flows I and II state that speeds of 50 mph or more and 45 to 50 mph, respectively, "are attainable." Whether these speeds refer to all vehicles, weaving vehicles, or nonweaving vehicles is not clear. It is assumed that only weaving vehicles are included as criteria because quality of flows III, IV, and V (40 to 45 mph, 30 to 35 mph, <30 mph, respectively) specifically refer only to these.

Level of service criteria are similarly unclear, with HCM suggesting that speeds in weaving sections for a given level of service be 5 to 10 mph lower than on similar sections with no weaving, or on the highway proper. Standards are taken from HCM Table 9.1 (freeways) or corresponding tables. Because these tables refer to the average speed of all vehicles, it is assumed that all vehicles are likewise included in the application of adjusted standards to weaving areas.

Also of concern is the discontinuity in both level-of-service and quality-of-flow criteria for speeds of 35 to 40 mph. As several of the analyses reported herein required determinations of level of service and quality of flow, standards were adjusted to provide continuous boundaries. For level of service in weaving areas, 10 mph was deducted from standards for the highway proper. The standards utilized are summarized in Table 1.

Quality of Flow—Level-of-Service Relationships

Table 7.3 of HCM details a relationship between level of service and quality of flow that is presumed to be consistent. However, consideration of the parameters that determine each when using the procedure in analysis shows that no consistent dependence of one on the other exists. Analytically, quality of flow as determined by the weaving chart depends upon the weaving volume and the length of the segment. Level of service depends upon the service volume, which is found by dividing the total expanded volume by the number of lanes. Although these parameters are loosely related, it can be seen that specification of a quality of flow does not automatically yield a level of service or vice versa. The full range of quality of flow–level of service combinations is theoretically feasible, and conditions actually occurring are not restricted to those combinations shown in HCM Table 7.3.

TABLE 1

SERVICE CRITERIA FOR EVALUATION OF THE INTERNAL STRUCTURE, HCM PROCEDURE 1

LEVEL OF SERVICE	SMS (MPH) OF ALL VEHICLES: ON FREEWAYS	SMS (MPH) OF ALL VEHICLES: IN WEAVING AREAS	QUALITY OF FLOW	SMS (MPH) OF WEAVING VEHICLES
A	≥ 60	≥ 50	I	≥ 50
B	55 to 60	45 to 50	II	45 to 50
C	50 to 55	40 to 45	III	37.5 to 45
D	37.5 to 50	27.5 to 40	IV	30 to 37.5
E	30 to 37.5	20 to 27.5	V	< 30
F	< 30	< 20	—	—

These observations are supported by data from the BPR data base. If actual qualities of flow and levels of service are identified by sample speeds, fifteen of forty-five experiments reveal combinations not indicated in HCM Table 7.3. Because the space mean speed (SMS) of all vehicles numerically includes the SMS of weaving vehicles, even those experiments which conform to HCM may be more indicative of a computational dependence rather than a real interrelationship between flows.

The unrestricted nature of the level-of-service–quality of flow relationship can be seen in both analysis and design. Consider, for example, a weaving configuration long enough to be "out-of-the-realm-of-weaving." Such a section may conceivably operate at quality of flow I as analytically determined by V_{we} and L, but will experience the full range of levels of service based upon total volume fluctuations. Due to the great length of such a section, weaving volumes may never be high enough to deteriorate the quality of flow. While analytic determinants may indicate quality of flow I and level of service D, for example, the high weaving speeds predicted for quality of flow I will not be achieved because total volumes restrict the entire operation to level of service D.

In design, a similar situation is encountered. When the width equation (Eq. 1) $N = [V + (k - 1)\ V_{w2}]/SV$ yields fractional results, additional length may be provided (this lowers k) to reduce N to the nearest whole number. In this way, a more economical design is achieved. However, as the length is increased, a better quality of service is attained. Level of service, on the other hand, remains unchanged.

It can be seen that the analytic relationship between level of service and quality of flow is unrestricted. In the use of these measures in analysis, it is necessary to determine which of the two measures gives a more realistic description of operations. In general, this will be the "worst case," as in the example above where quality of flow I could not actually be achieved due to the low level of service. Because the general level-of-service design for a given facility is of primary interest, the quality-of-flow design for weaving areas should be as good as or better than the design level of service.

A Recommended Descriptor of Service

In the previous item, it was pointed out that no functional analytic relationship exists between quality of flow and level of service. It was also stated that actually occurring values do not conform to the relationship predicted by HCM. It was further pointed out that the inclusion of all vehicle speeds in the level-of-service description may mask significant differences between weaving and nonweaving flows. Such differences often occur, as is indicated by examination of experiments of the BPR data base.

As substantial differenecs in the speed of weaving and nonweaving often occur, it would appear that separate levels of service for weaving and nonweaving vehicles would be more descriptive of actual operating conditions.

Geometric Effects

Drastic differences in weaving and nonweaving speeds occur in some cases and not in others. Investigation indicates that geometric configuration is a major factor. Table 2 data show that speed differences occur most often on ramp-weave sections and that the differences are generally larger than those observed for other configurations. In the ramp-weave configuration, weaving vehicles are more or less restricted to two lanes—the auxiliary lane and the shoulder lane. Additional lanes in ramp-weave sections will be used primarily by nonweaving vehicles. Where total width is excessive, weaving vehicles may operate at low speeds in two lanes while outer flows travel at considerably higher speeds in other lanes. The geometry of the ramp weave restricts weaving vehicles primarily to two lanes, regardless of the total number of lanes provided. Major weaves, which vary widely as to configuration, are generally not as restrictive. The subject of configuration is discussed in some detail in the later section on "Development of a Weaving Procedure." It may be said, however, that the HCM approach of computing total lane requirements may be misleading. Lane requirements for weaving and nonweaving flows should be separately computed so that a configuration allowing an appropriate lane usage may be designed.

Development of the Weaving Chart

The original data and rationale used to produce the weaving chart have not been documented and are no longer available for study. However, certain facts concerning the development of the chart are known and can be commented on.

The original weaving chart of the 1950 HCM involved three plots on a V_{we} versus L field. One plot was for maximum possible capacity, one for 30-mph operating speed, and one for 40 mph. These three curves were based on field data and were adjusted slightly in a 1957 article by O. K. Normann (*3*). These three curves became curves III, IV, and V in the 1965 HCM. The original equation for width was similar to the present one but contained a constant expansion factor of 3.0 rather than a variable k based on V_{we} and L. Conversations with principals involved with its development indicated that the 3.0 expansion factor was rationalized on the basis of approximate gap size necessary to execute a weaving maneuver and was not based on observed data. By the time the 1965 HCM was being formulated, limited amounts of data permitted estimation of curve I for "out-of-the-realm-of-weaving." For this curve, the expansion factor was logically 1.0. This left the problem of providing a smooth expansion transition from 1.0 below curve I to 3.0 above curve III. The intermediate curves of the 1965 HCM are the results of a constructed transition.

Therefore, while the length–weaving volume relationships depicted by curves I, III, IV, and V of the 1965 HCM weaving chart are based on limited amounts of data, the k-factor expansion mechanism has not been subjected to calibration.

The Range of k-Values

Freeway experiments of the BPR data base were used to calibrate and verify the constant k-curves of the weaving chart. Using the width equation with all values known except k, k can be computed as:

$$k = \frac{N\,(SV)}{V_{w2}} + \left(1 - \frac{V}{V_{w2}}\right) \qquad (2)$$

in which terms are as defined for Eq. 1. Service volume is given in HCM Table 9.1 for each level of service as identified by the SMS of all vehicles (the speed criteria of Table 1 are used).

A problem arises in that only integer values of N are observed, whereas fractional values may be obtained in design. Thus a "round-off" error may exist that causes inflated values of k to appear. These errors arise, however, because SV is treated as a step function with one value for a range of speeds. In actuality, all lanes are used. If a fractional part of a lane has been added to the design computation, speeds slightly higher than the minimum for the level of service used will result. Therefore, if the values of speed given in Table 1 herein and the SV values of HCM Table 9.1 are viewed as threshold values between which is a straight-line interpolation, a SV based on the exact observed speed can be selected and the round-off error eliminated.

TABLE 2

WEAVING AND NONWEAVING SPEEDS FROM THE 1963 BPR STUDY

TYPE OF SECTION	SMS OF NONWEAVING VEHICLES IS —— THAT OF WEAVING VEHICLES: MORE THAN 5 MPH LOWER THAN	WITHIN 5 MPH OF	5 TO 10 MPH HIGHER THAN	10 TO 15 MPH HIGHER THAN	MORE THAN 15 MPH HIGHER THAN
Ramp weave	1	10	0	2	4
Major weave collector-distributors	2	17	4	1	0
All	3	27	4	3	4

If step-function SV values are used, it is possible to compute the maximum round-off error for each experiment. Accordingly, k-values were computed by this means. For sixteen ramp-weave cases, k took on three values above 3.0 and four below 1.0. Of nineteen major weaves, eight values were significantly above 3.0 and one was below 1.0.

Values below 1.0 are disturbing because it does not seem feasible that a vehicle among V_{w2} is equivalent to less than 1.0 other vehicles and certainly does not occupy negative space. Values below 1.0 may be the result of such unusual geometric conditions as sharp loop ramps or extra wide lanes. In this latter case, a 72-ft roadway was striped for five lanes although vehicles had room to form six. Sampling errors may have also influenced these values.

Despite this concern, the upper limit of 3.0 has most certainly been shown to be false because eleven of twenty-six computed k-factors are beyond this limit. The calibration, however, does not clearly indicate or suggest any other upper limit on k.

The Relationship of k to V_{wc} and L

The k-factors were plotted on the V_{wc} versus L field in an attempt to reestablish the constant k-curves of the 1965 HCM weaving chart. This plot is shown in Figure 4. The plot shows that no such constant k-curves exist and that the relationship between k, V_{wc}, and L is not as is depicted in the HCM.

The Expansion Concept

Before discarding the basic idea of an equivalence expansion mechanism, a number of possible alternatives were examined. Two additional sets of expansion factors k_{V_w} and $k_{V_{w1}}$ were computed based on expansion of the entire weaving volume V_w and the larger weaving volume V_{w1}. These were plotted on the V_{wc} versus L field and, as in the case of the k-factors, no constant value curves were formed. However, all three expansion constants k, k_{V_w}, $k_{V_{w1}}$ exhibited promising correlations when plotted versus the ratios V_w/V_T and V_{w2}/V_{w1}. While these results were not conclusive, they suggest two things about the "true" expansion mechanism—expansion of both V_{w2} and V_{w1}, perhaps individually in an additive fashion, should be considered; and, the expansion value seems to depend on both the percentage of weaving vehicles in the traffic stream and the split between V_{w1} and V_{w2}. A predictive mechanism for k, therefore, should involve both parameters. It is concluded that a valid expansion model would be far more complex than that used in the 1965 HCM. The data at hand are not sufficient to investigate possible forms. Because of the difficulties involved in collecting such data to calibrate a model of undetermined form as well as the difficulties involved in formulating such a model, it appears that development of a design procedure that does not directly involve equivalence expansion would be advisable.

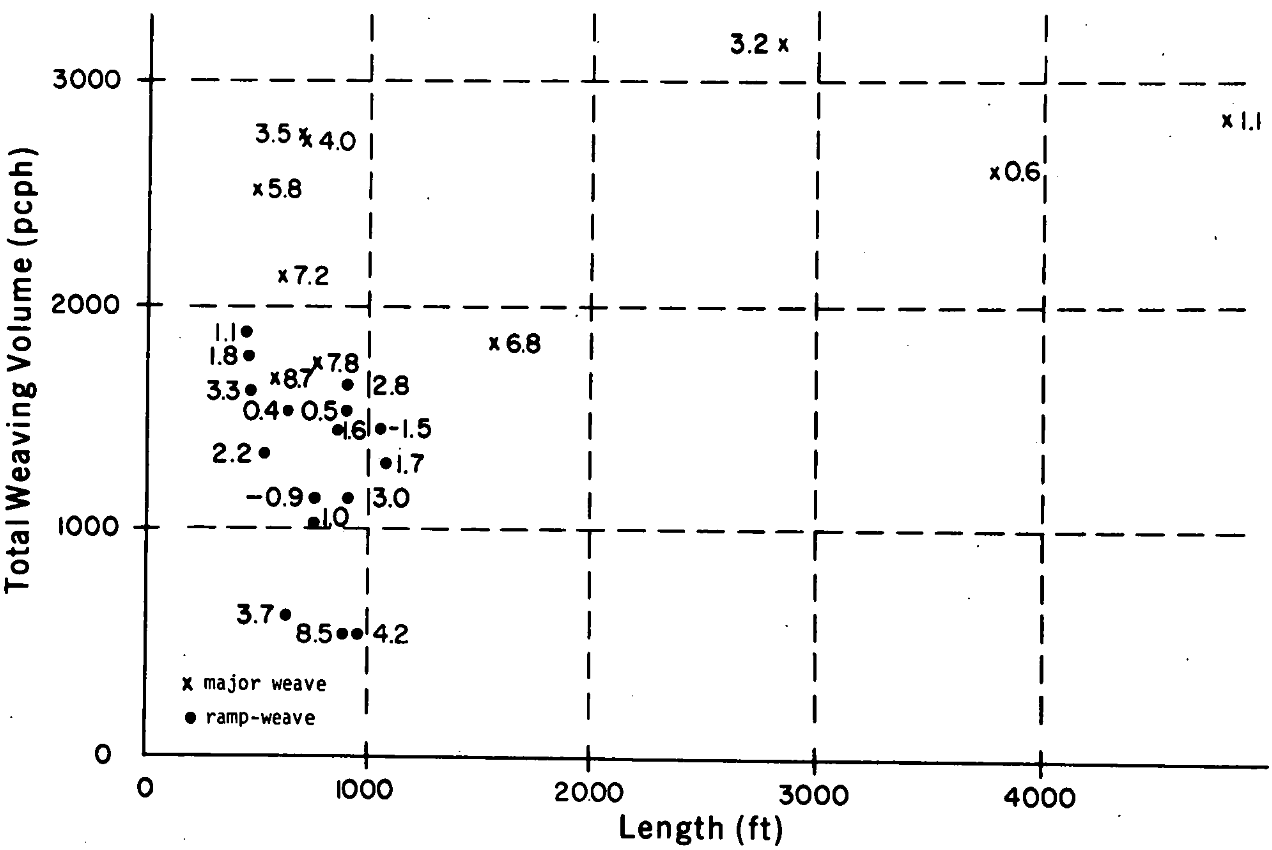

Figure 4. Plot of computed k*-factors on a weaving chart.*

ANALYSIS OF THE ACCURACY OF HCM PROCEDURES

This discussion concerns the results of the accuracy analysis of the HCM procedures. The two prime areas of analysis are (1) level-of-service accuracy of the three procedures and (2) lane 1 volume prediction accuracy. Other elements related to procedures 2 and 3 are discussed. Additional details of these analyses are given in Appendix V.*

The fact that the data base for procedure 2 was available allowed some additional analysis. This work was done in the context of the first phase of this project, when part of the project effort might also have been devoted to restructuring a ramp treatment in light of the (eventual) outcome of the weaving studies of the present research. It was primarily concerned with the question of whether a fewer number of cases could have been used in procedure 2. The results reaffirmed that the cases enumerated were indeed statistically distinct as formulated. Estimates of the relative effectiveness of adding new data points to the several existing cases were made. Details are contained in Appendix XV.*

Level of Service Accuracy in the Three Procedures

It was decided, where possible, to test the accuracy of all three procedures in predicting actual levels of service observed in field experiments.

A problem immediately arises in that the speed–level-of-service relationships that must be used to identify field levels of service differ for the two HCM chapters. Procedures 2 and 3, from HCM Chapter 8, use the relationships of HCM Table 9.1 directly; procedure 1, of HCM Chapter 7, specifies a deduction of an ambiguous 5 to 10 mph from these standards. In the internal analysis of the weaving procedure 1, the researchers used the 10-mph deduction for consistency. For accuracy, a number of alternatives were tested, including one suggested by a principal in the development of HCM Chapter 7. Results indicated that this latter specification correlated best to predicted levels of service, so that only results for this case are reported. The speed–level-of-service relationships used in the accuracy analysis are summarized in Table 3.

The problem with the HCM in that level of service C means different standards depending upon the procedure used must be kept in mind when considering the results of the accuracy analyses.

The analysis considered basic weaving sections (in which all traffic weaves), ramp-weave cases, and major weave cases separately. Only in the case of ramp weaves can all three procedures be applied and compared. Only procedure 1 is used in other cases. Data from the BPR data base were utilized, both for peak-hour data and individual 6-min periods. The results of the analysis are summarized in Tables 4, 5, and 6.

The following conclusions may be drawn from these results:

- The accuracy of level-of-service predictions by procedure 1 is highest for basic weaving sections, followed by ramp weaves and major weaves. Accuracy of the procedure is generally poor—less than one-third of all experiments were accurately predicted. Use of operating speed would have further degraded the accuracy.
- For basic weaves and ramp weaves, the majority of errors are by a single level of service with no trend toward being poorer or better than actual values for procedure 1. When applied to major weaves, procedure 1 tends to predict levels of service poorer than actually occurring values.
- While the HCM recommends the use of procedures 2 or 3 for ramp-weave cases, procedure 1 produces more accurate estimates of level of service.
- Level-of-service predictions for ramp-weave cases by procedures 2 and 3 tend to be better than actual field conditions.

Lane 1 Volumes and Other Elements of Procedures 2 and 3

The accuracy of procedures 2 and 3 as regards ramp-weave cases was further investigated. These procedures depend on the prediction of lane 1 volumes in advance of ramps. Accordingly, lane 1 volumes were computed by procedures 2 and 3 immediately in advance of the on-ramp and were compared to actual volumes. While HCM recommends procedure 2 for cases of levels of service A, B, and C and procedure 3 for level of service D,* both methods were applied to all experiments where possible.

The accuracy of procedure 2 for cases of levels of service A, B, and C is shown in Figure 5. Differences between computed and observed lane 1 volumes ranged from 6 to 24 percent with an average difference of 15 percent. The sample size, however, was only four and definitive conclusions can not be reached.

Twenty experiments were determined to be in levels of service D and E. When lane 1 volumes were computed by procedure 3, the differences between observed and computed values ranged from 1 to 70 percent with an average of 25 percent. As shown in Figure 6, most errors involve computed values lower than actual values, a serious condition that may result in inadequate designs.

Thirteen of the twenty levels of service D and E cases were also examined by procedure 2, as shown in Figure 7. Differences between observed and computed lane 1 volumes ranged from 1 to 43 percent with an average of 17 percent, a distinct improvement over procedure 3 results. Despite the HCM specification of procedure 3 for these cases, lane 1 volumes were more accurately predicted by procedure 2 in ten of thirteen cases.

It should be noted that procedure 3 most properly applies only to level of service D. In its prescribed use, it is to check a given ramp-weave segment or ramp to see if it meets the requirements for the high-volume threshold of level D. The accuracy analyses referenced herein did in fact do this. When the criteria for level D are not met, level E was assumed. The method was extended to include a check versus Table 8.1 level E checkpoint values to determine whether a level F condition was indicated.

These results show that procedure 2 produces more ac-

* Not included in this publication. See Appendix J herein for additional information.

* It is also commonly applied to level of service E.

TABLE 3

SERVICE CRITERIA FOR ACCURACY ANALYSIS OF HCM PROCEDURES

LEVEL OF SERVICE	SMS (MPH) OF ALL VEHICLES FOR: PROCEDURE 1	PROCEDURES 2 AND 3
A	≥ 50	≥ 60
B	45 to 50	55 to 60
C	37.5 to 45	50 to 55
D	25 to 37.5	37.5 to 50
E	15 to 25	30 to 37.5
F	≤ 15	≤ 30

curate levels-of-service predictions than procedure 3 for ramp-weave cases with auxiliary lanes, even for cases of levels of service D and E. To further examine the accuracy of procedure 2 for all levels of service, 6-min data were used. An average difference between observed and computed lane 1 volumes of 19 percent was obtained. A general trend toward decreasing accuracy as length of the section increases was noted. The angle of approach at on-ramps was also investigated, but results indicated that it had little effect on the accuracy of lane 1 volume predictions in the normal range of 1 to 6 degrees.

The accuracy of HCM Figure 8.22, which predicts the percentage of trucks in lane 1, was also tested. Differences between observed and actual values ranged from 1 to 37 percent with an average of 13 percent. Particularly in the case of eight-lane freeways, the results predicted by HCM are markedly different from a regression line fit to the actual data. This is shown in Figure 8. While the differences noted for four- and six-lane freeways are not as drastic, HCM Figure 8.22 does not appear to accurately represent the relationship between freeway volume and percentage of trucks in lane 1.

CONSISTENCY OF THE HCM PROCEDURES IN SPECIFYING LEVEL OF SERVICE

The consistency of the three procedures in specifying levels of service was examined by comparing predictions for ramp-weave cases of the BPR data base. To obtain a comparison over a wider range of levels of service, a range of cases was also constructed and analyzed. The results of the analysis indicate that procedure 1 yields level-of-service estimates poorer than procedures 2 and 3 for relatively short or wide sections and better levels of service than procedures 2 and 3 for longer, narrower sections. These

TABLE 4

ACCURACY OF PROCEDURE 1 IN PREDICTING LEVEL OF SERVICE FOR BASIC WEAVING SECTIONS

		HCM COMPUTED LEVEL OF SERVICE IS:				
					MORE THAN ONE LEVEL	
	TYPE OF DATA	SAME AS (%)	ONE LEVEL BETTER THAN (%)	ONE LEVEL POORER THAN (%)	BETTER THAN (%)	POORER THAN (%)
Actual level of service based on SMS of all vehicles	Peak hour *	50	16	16	—	16
	6 min	30	34	17	8	11

* Sample size only 6 experiments.

TABLE 5

ACCURACY OF PROCEDURES IN PREDICTING LEVEL OF SERVICE OF RAMP-WEAVE SECTIONS (PEAK-HOUR DATA*)

		HCM COMPUTED LEVEL OF SERVICE IS:				
					MORE THAN ONE LEVEL	
	HCM PROCEDURE NO.	SAME AS (%)	ONE LEVEL BETTER THAN (%)	ONE LEVEL POORER THAN (%)	BETTER THAN (%)	POORER THAN (%)
Actual level of service determined by SMS of all vehicles	1	35	23	35	7	—
	2	23	41	12	24	—
	3	20	40	—	40	—

* Similar results are obtained with 6-min data.

TABLE 6

ACCURACY OF PROCEDURE 1 IN PREDICTING LEVEL OF SERVICE OF MAJOR WEAVES AND OTHER MISCELLANEOUS CONFIGURATIONS

		HCM COMPUTED LEVEL OF SERVICE IS:				
					MORE THAN ONE LEVEL	
	TYPE OF DATA	SAME AS (%)	ONE LEVEL BETTER THAN (%)	ONE LEVEL POORER THAN (%)	BETTER THAN (%)	POORER THAN (%)
Actual level of service determined by SMS of all vehicles	Peak hour	27	—	69	4	—
	6 min	21	7	43	4	25

general results, however, must be viewed in light of the fact that level-of-service criteria for procedure 1 differ from those for procedures 2 and 3. Because of this problem, the results of the accuracy analyses must be viewed as the more meaningful.

Details of these analyses are contained in Appendix V.*

CURRENT PRACTICES

The research agency sent questionnaires on current practices in design and analysis of weaving sections to the fifty states and to thirty-five major consultants in December 1971. A total of fifty-one responses—thirty-eight states and thirteen consultants—were received.

Several states and consultants responded with detailed comments on the present HCM, as well as forwarding completed questionnaires. Several of them also offered comments on the Summary Report of the first phase of NCHRP Project 3-15 "Weaving Area Operations Study," which was attached to the questionnaires for information. Because many of the consultant replies indicated that they follow state practices, only a summary of responses from the states is included herein. The major points are:

- There is a difference of opinion whether Chapter 7 or Chapter 8 of the HCM should be applied to weaving areas of the ramp-weave type. More use Chapter 7, despite the fact that the HCM recommends Chapter 8.†
- The HCM is used more for analysis than for design.
- The HCM is used more than the AASHTO "Blue Book" for both analysis and design.
- Of the respondents, 81 percent were satisfied with the HCM but a number offered specific comments and recommendations.
- When using whatever standard procedure was cited, most respondents (83 percent) applied some modification or restriction. Of these, 54 percent (44 percent of the total) involved minimum lengths. Also, 38 percent (32 percent of the total) involved the level of service–quality of flow relationship. In both cases, "engineering judgment" was cited a number of times as the criterion.

* Not included in this publication. See Appendix J herein for additional information.

† The HCM, however, has ramp-type problems in the examples of Chapter 7.

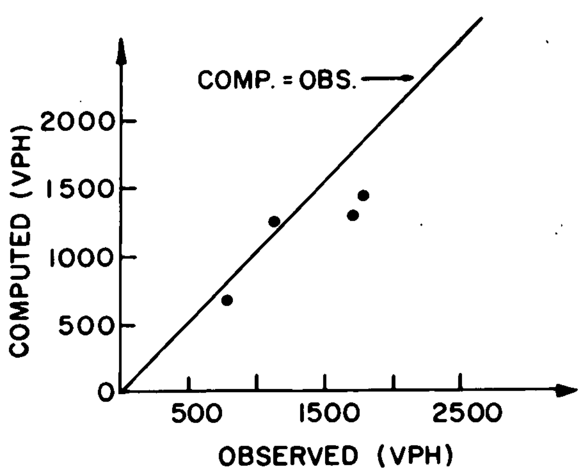

Figure 5. Plot of peak-hour data showing computed versus observed lane 1 volumes for levels of service A, B, and C, procedure 2.

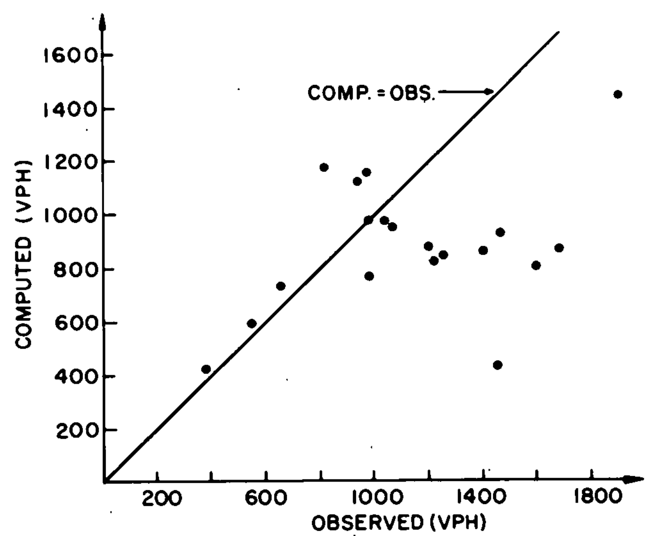

Figure 6. Plot of peak-hour data showing computed versus observed lane 1 volumes for levels of service D and E, procedure 3.

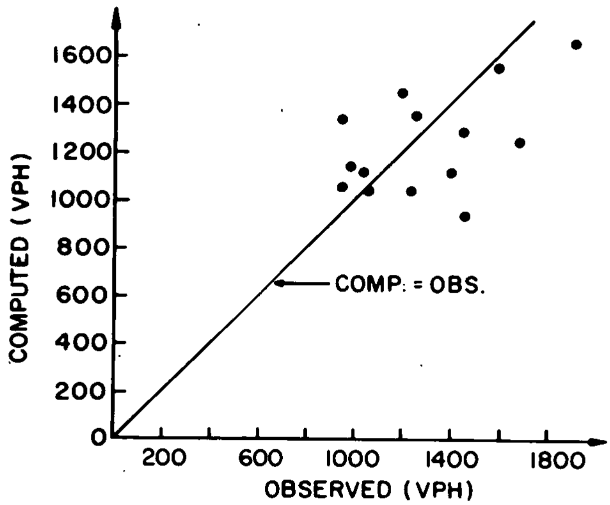

Figure 7. Plot of peak-hour data showing computed versus observed lane 1 volumes for levels of service D and E, procedure 2.

The results indicate that some uses contrary to HCM recommendations exist and that specific additional design items do exist. For instance, ten respondents cited specific minimum length practices. At the same time, potential ambiguities exist. For example, 32 percent of those responding to the question indicated that a weaving section is designed to a lower level of service than the through roadway. However, this is already "built into" procedure 1, so that it would be designed to operate poorer than intended.

This survey documents the wide utilization of the HCM weaving procedures, while highlighting the fact that variations in its use do exist, and that problems are recognized. Appendix B contains a detailed summary of the survey responses.

DEVELOPMENT OF A WEAVING PROCEDURE

Based on the evaluation of the existing procedures, the researchers recommended to NCHRP a study program. The program centered on the generation of a new weaving area design/analysis procedure and the requisite data collection associated with this objective. A concurrent effort to better expose the basic mechanisms and elemental considerations of weaving was also recommended.

This section presents the prime findings and results related to the development of that new procedure. The procedure is presented in a self-contained, user-oriented form in Appendix E, which includes a number of examples, both design and analysis.

Appendix E document was circulated to potential users in five state organizations (i.e., Connecticut, Massachusetts, New Jersey, New York, and Pennsylvania) in accordance with the researchers' approved program, for the purpose of eliciting comments (not necessarily endorsements) on its ease of use and clarity. Three reactions were received; they were favorable.

Appendix C contains details of the configuration analysis cited herein.

Appendix D contains details of the calibration of the basic relationships, including the development of the form of these relationships. The development was supported and substantiated by microscopic considerations to the maximal extent possible.

Appendix F presents a computer program by which the required computations may be done. The program is written in FORTRAN IV. The appendix includes examples, input format, and possible error and warning messages.

General

The following are some of the general concepts or ideas integral to the procedure:

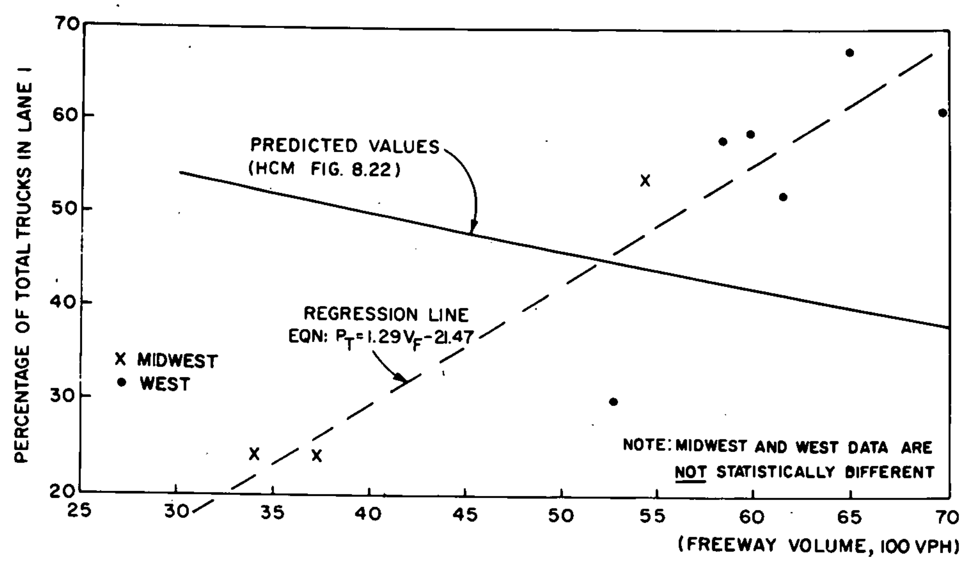

Figure 8. Plot to test accuracy of predicted data, supplied by HCM Fig. 8.22, versus observed data shows a marked discrepancy.

• Space mean speeds (SMS) rather than operating speeds are used to define levels of operation.

• The service volume (SV) concepts of the HCM are adapted and used for the nonweaving traffic.

• Volumes are considered in passenger car equivalents (pce) in units of passenger cars per hour (pcph). Adjustments of vehicles per hour (vph) to pcph is made in accordance with the HCM.

• Levels of service are defined separately for weaving and nonweaving flows.

• Although balanced design (comparable level of service) is sought, it is recognized that configuration may prevent it from being realized.

• As far as basic relationships are concerned, there exist two sets of equations—one for major weave sections and one for ramp-weave sections.*

• The definitions of variables and terminology are contained in Chapter One.

Configuration

The explicit consideration and awareness of configuration (section lane arrangement, including numbers of lanes on each leg) is an important and essential element of the recommended weaving procedure. All else that is done should be done in this context.

It is of prime importance in design that the configuration be such that:

• The computed W can in fact be delivered.

• The lanes required for each outer flow (nonweaving flow) can in fact be delivered.

• The lanes on each input/output leg can, in fact, handle the volumes at the level of service desired.

One of the prime results of the research leading to the recommended procedure was the determination that there is a maximum width that can, in fact, be used by weaving traffic. It was found that this depended upon configuration type. The results are summarized for use in Table 7. The various configurations cited are shown in Figure 2.

Since it is generally accepted that a "choice lane" should be provided for a major weave-type configuration, most designs will automatically incorporate a through lane (Figure 2 (C) or (D), which have choice lanes at the bifurcation proper, as opposed to Figure 2 (B), which does not). It does not follow that this will necessarily correspond to the direction of the greater weaving flow at all times. The benefit of $W = 3.6$ is only realized completely, however, when it does correspond.

In analysis, knowledge of the configuration (lane arrangement) and Table 7 dictates the maximum W. It also provides information on the adequacy of the section for its nonweaving (outer) flows.

Appendix C addresses the matter of configurational constraints in three ways:

• Rational development of constraint numbers and confirmation from peak-hour data of the BPR data base.

* Recall that a major weave has three or more legs each having two or more lanes. A ramp weave is a standard auxiliary lane arrangement with one lane on and one lane off. The basic types are shown in Figure 2.

TABLE 7

MAXIMUM WEAVING WIDTH W VARIES WITH CONFIGURATION [a]

CONFIGURATION	WIDTH (LANES)
Ramp weave	2.3
Major weave with a crown line	2.6 to 2.7 [b]
Major weave with through lane on direction of greater weaving flow	3.6

[a] See Figure 2.
[b] An estimate. The data base was deficient in these cases.

• Further confirmation from the 18-min composite data base (which includes the project data base).

• Support by a lane-changing model.

The lane-changing model verifies that the lane arrangement (configuration) is important. This model, formulated to check this one aspect, lacks an internal capacity limit. Another formulation, presented in Appendix H, is more realistic in this respect. It too confirms that there is a configurational effect.

This appendix also addresses configuration/lane arrangement from the aspect of lane balance, reinforcing the above analyses.

Use of Space Mean Speed (SMS)

Operating speed is defined in the HCM as "the highest over-all speed at which a driver can travel on a given highway under favorable weather conditions and under prevailing traffic conditions without at any time exceeding the safe speed as determined by the design speed on a section-by-section basis." It is the fastest reasonable speed. Space mean speed, on the other hand, is "the average of the speeds of vehicles within a given space or section of roadway at a given instant," or "the average speed of a specified group of vehicles based on their average travel time over a section of roadway."

Space mean speed has the advantage of having an operational definition; that is, it can be measured unambiguously. Moreover, most data are in fact collected in ways that yield space mean speeds, not operating speeds. This includes most speed–volume data that underlie curves of the service volume–speed relation. In regard to weaving analysis, the 1963 BPR data base could only meaningfully yield space mean speeds.

Because of both the exigencies of the data base(s) available and the more basic judgment that operating speed is unnecessarily ambiguous as to measurement, space mean speed was adopted as the speed measure. The question was raised of how the service volume–speed relation of the HCM could have been calibrated with operating speeds. For low speeds in the data at hand, the space mean speeds approached the speeds expected in the HCM.

In the recommended procedure, space mean speeds were the ones used. The calibration and use are consistent within the recommended procedure, and the procedure is self-contained in this respect. Comparisons with the HCM are done on the basis of (service) volumes in the examples and not speeds alone.

Should the user wish to obtain operating speed estimates, however, he can use the formula developed by Makigami, et al. (*6*):

$$OS = AS + \frac{DS}{10}\left[1 - \left(\frac{V}{C}\right)\right] \quad (3)$$

in which

OS = operating speed (mph);
AS = average running speed or space mean speed;
(DS) = design speed or speed limit (mph); and
V/C = volume-to-capacity ratio.

With a 55-mph speed limit and $V/C = 0.40$, the increment is 3.3 mph. This is at level of service A for a six-lane facility (three lanes per direction). At level of service B, the increment would only be 2.3 mph.

Development of the Basic Relationships

Extensive analysis of both the macroscopic data (6-min or greater flows and speeds) and the microscopic data and models developed within this research project led to development of the regression-based relationships that form the core of the recommended procedure. A number of macroscopic forms were considered. All were postulated and/or reviewed with due consideration of the microscopic aspects, data, and models. However, the final direction and calibration emphasized the macroscopic in the interest of acquiring a wide data base at practical cost.

Appendix D contains the details of the development of the macroscopic forms and the final calibration. It also includes an analysis, using the procedure developed, of some data reserved from the project data base for that purpose. Some characteristics of the calibration, beyond those already noted, are:

- The distinction between ramp weaves and major weaves was determined as necessary in the course of the calibration.
- The proper range of the calibration is found to be for nonweaving speeds (S_{nw}) of 30 mph or greater. This limit, the common limit for level of service E, is found as a result of the investigation, not as an a priori assumption.
- For major weaves, it is found that the weaving speed (S_w) can go as low as 20 mph for $S_{nw} \geqq 30$ mph. This can be, and is, used to define a lower limit for weaving level of service E.
- The resulting relationships include S_{nw} and S_w explicitly (sometimes via $\Delta S = S_{nw} - S_w$), so that a continuum results rather than subcases for each of a set of levels of service, which would be somehow defined. As a result, levels of service can be, and are, specified exogenously. The researchers selected definitions that consider existing usages.
- Data aggregated in 18-min time periods yielded better regularity than 6- or 12-min periods. Longer periods did not improve the regularity but did reduce the number of data point available. The calibration is based on 18-min time periods.

The best relationships describing weaving traffic were developed starting from the assumption that W/N is proportional (actually, functionally related) to VR. That is, that the percentage of width required by weaving vehicles is directly related to the percentage of the total traffic that they constitute.

Note that this one relationship—W/N dependent principally upon VR—involves both types of flow (weaving and nonweaving) in the determination of W. This is reasonable, for although the flows are significantly segregated as they enter the section, there is a physical overlap and thus interaction in the space they occupy.

The basic relationships for both major weaves and ramp weaves are summarized in Table 8. Each configuration type (major weave or ramp weave) is subject to two governing equations:

TABLE 8

RELATIONSHIPS OF MAJOR AND RAMP WEAVES

EQUATION TYPE	EQUATION DETAILS	EST. OF CORR. COEFF.
	(a) MAJOR WEAVE	
Primary	$\log\frac{W}{N} = -1.16 + 0.660\,VR - 3.10\,R(\log VR)e^{-0.1L} + 0.372\log S_w$	$\rho = 0.812$
Secondary (holds only if W not constrained)	$\Delta S = 48.3 - 27.4\log S_w - 0.146\,L$	$\rho = 0.637$
	(b) RAMP WEAVE	
Primary	$\Delta S = -109.5 + \frac{104.8}{\sqrt{L+3}} + 50.7\log S_{nw}$	$\rho = 0.787$
Secondary (holds only if W not constrained)	$\log\frac{W}{N} = -0.615 + 0.606\sqrt{VR} - 0.00365\,(\Delta S)$	$\rho = 0.757$

1. A "primary relationship" that holds under all conditions and was calibrated with all available data. Note that the sample correlation coefficient is in the order of 0.8 in both cases.
2. A "secondary relationship" that holds only when W is not configuration constrained and that was calibrated with only those data that did not border on configuration-constrained.

The ramp-weave secondary relationship in particular would be significantly weaker if an attempt were made to fit it with all available data.

The importance of the secondary relationship is in removing an indeterminacy that superficially seemed to exist. Without them, analysis of a section could not yield a specific, most probable description of operations unless W was at its maximum. They are secondary only in that they do not always hold.

The fact that the relationship defining ΔS is of greater importance for ramp weaves than for major weaves is logical. In a ramp-weave situation, even one in which W is constrained, ΔS is dependent upon the runway provided to the weaving vehicles (this is determined by L), and—for a given L—the weaving flow is carried along to a certain extent by the motion, speed, and opportunities of the mainline. Whenever possible, W will readjust to suit the situation at hand, as is reflected in the secondary equation for ramp weaves.

It is interesting that the length L is a significant determinant of section operation but that its significance dissipates quickly as L is increased. In both major weaves and ramp weaves, by far the greatest part of the advantage of length is achieved by 2,000 ft.

It should be noted that there were no ramp weaves above 2,000 ft used in the calibrations, nor are they often built. The utility of such added length is not related directly to weaving section performance; perhaps a ramp weave is merited that needs only be 1,500 ft long, but external considerations dictate ramp locations that cause a 2,500-ft length.

In the case of the major weave, there is still benefit above 2,000 ft in increasing length, although most of the benefit would have already been realized. While the calibration data base contains lengths up to 4,600 ft, only 10 percent of the base is above 2,000 ft. One should expect less precision in the results for rather long sections.

It is possible to show that as the major weave section is made very long the level of operation does not generally reach the level defined by $SV = V_{TOT}/N$ (effective nonweaving). Although this may be due to the limitations of the calibration, it must be remembered that (1) the merge and diverge turbulence will always exist regardless of length, and (2) there is intensive lane changing at the beginning of the section because of intensive presegregation, which adds to/causes the turbulence.

In regard to which set of equations should be used for which design problems, it must be recognized that the flows and the VR value will generally give insight into which configuration type should be used in a particular design problem. In analysis, inspection of the configuration will generally determine the relations to use.

Levels of Service; Service Volumes

In accordance with the above-cited results, a set of level-of-service definitions were established. Consistent with the thoughts underlying the calibration, separate standards were defined for weaving and nonweaving traffic.

The levels of service as defined in the HCM Table 9.1 were adapted for use with the nonweaving volumes. The adaptations were that (1) space mean speeds rather than operating speeds are used throughout, including the calibrations; (2) the service volume values were interpolated between those commonly specified as necessary, the interpolation being linear with respect to travel times; and (3) the boundary between levels D and E was taken as 38 mph.

The characteristics of the definitions are:

- The nonweaving level of service for both major weaves and ramp weaves will be defined analogous to the HCM as discussed above.
- The weaving level of service for ramp weaves will be defined identical to the nonweaving level of service.
- The weaving level of service for major weaves will be defined so that, at "balanced" or equilibrium operations, both nonweaving and weaving traffic will have the same level-of-service designation.

The last definition is achieved by observing the balance that occurs between weaving and nonweaving flows when W is not constrained by configuration. The speed differential that then exists is shown in Figure 9, which is based on the calibration data base.

Although the speed difference ΔS implied in Figure 9 is dependent on length as well as S_w, it is not highly sensitive to length. The curve for $L = 12.5$ is therefore used rather than adding an unnecessary complexity.

The level-of-service definitions are contained in Table 9. Note that level of service D is subdivided for major weaves

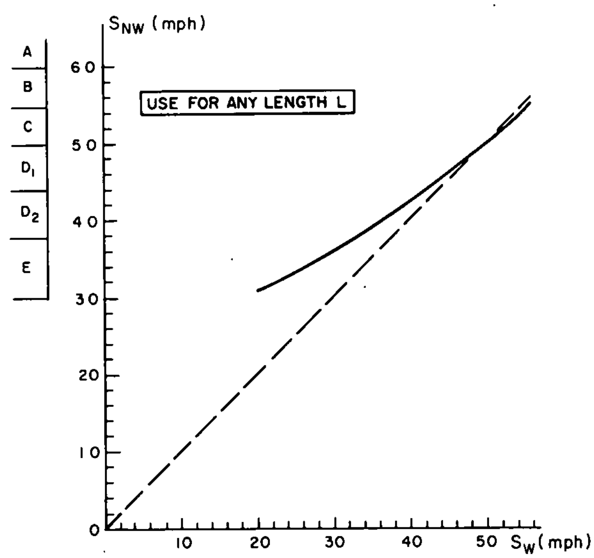

Figure 9. Speed relationships for major weave, design case.
Note: Insensitivity to L exhibited in ΔS formula (Table 3) generating this relationship. Curve shown for $L = 12.5$. This does not imply insensitivity to L in a major weave. See Table E-3.

TABLE 9

LEVEL-OF-SERVICE DEFINITIONS

LEVEL OF SERVICE	NONWEAVING (ALL) AND RAMP-WEAVE WEAVING RANGE (MPH)	NONWEAVING (ALL) AND RAMP-WEAVE WEAVING DESIGN SPEED (MPH)	MAJOR WEAVE (WEAVING TRAFFIC ONLY) RANGE (MPH)	MAJOR WEAVE (WEAVING TRAFFIC ONLY) DESIGN SPEED (MPH)
A	60 and up	60	60 and up	—[a]
B	55 to 60	55	55 to 60	55
C	50 to 55	50	50 to 55	50
D	38 to 50	—[b]	33 to 50	—[b]
E	30 to 38	30	20 to 33	20
F	30 and under	—	20 and under	—

[a] Improbable; no such case observed in the calibration data base; use procedure with this awareness.
[b] For ramp-weave: 38 mph
For major weave:
D_2: $\Delta S=5$: $S_{nw}=38$ and $S_w=33$
D_1: $\Delta S=2$: $S_{nw}=44$ and $S_w=42$

so that either $\Delta S = 5$ mph or $\Delta S = 2$ mph can be specified in design.

Note that one level of service characterizes both nonweaving flows. For a given design, the practitioner may observe that one is not accurately portrayed. For instance, a small ramp-to-ramp flow on a ramp weave is controlled by the weaving level of service. Other than this case (which will not significantly affect the computations), this refinement is not generally recommended as what is desired is a descriptor of the over-all section in relatively simple terms consistent with accuracy.*

The service volumes associated with the nonweaving levels of service are summarized in Figure 10. As noted, they are based on HCM values with linear interpolation (with respect to travel times) used to find values between those specified.

The service volume characterizing a section is to be based on the entrance leg with the greater number of input lanes. This is the approach used in handling the calibration data. In addition to determining N_{nw}, the service

* Moreover, one would frequently become enmeshed in considerations of "how much" of the W is on "which side" of the section, which requires a sophistication inappropriate to the purpose of the procedure. Insights can be gained, however, by the more sophisticated user.

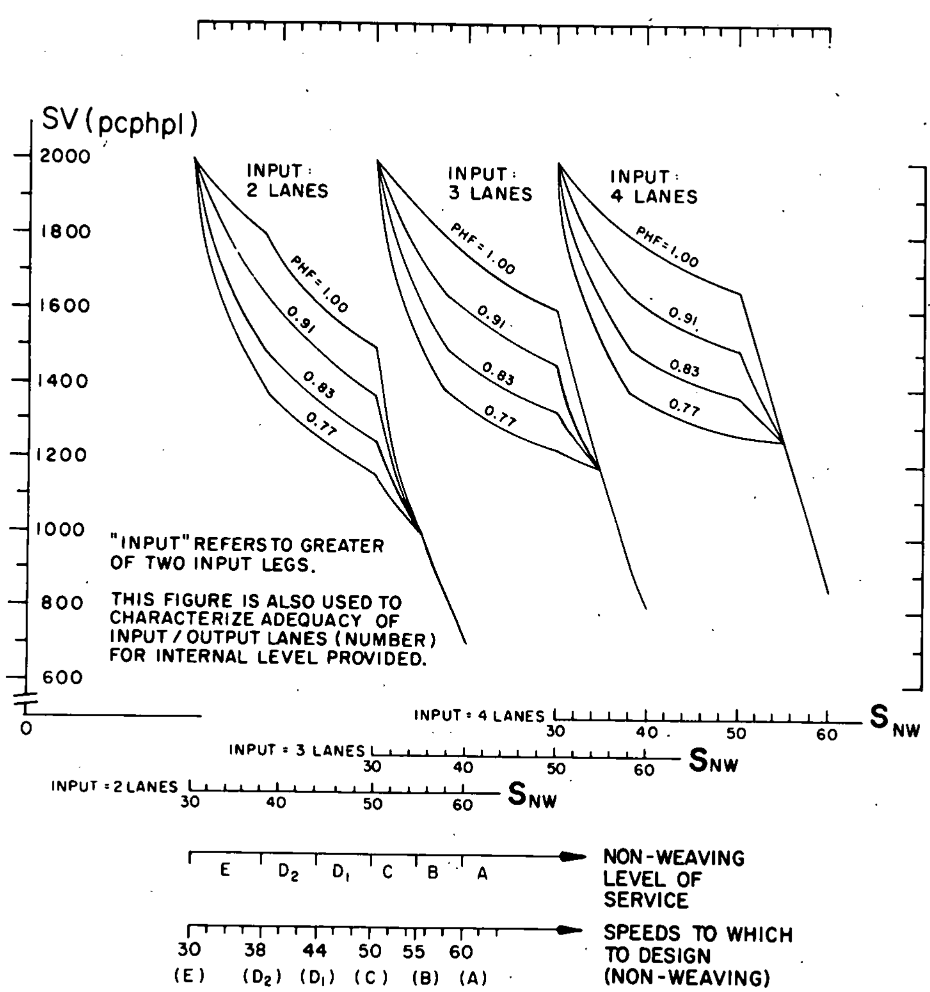

Figure 10. Service volumes accommodated for various specified values of S_{nw}.

volume is to be used in checking the input/output lanes required, or the adequacy of those provided.

Note that service volume is in pcphpl. All computations assume that the volumes have been adjusted for grade, trucks, lane width, and lateral clearance. The peak-hour factor (*PHF*) is built into the service-volume curves. It is as defined in the HCM.

The Structured Procedure

Appendix E is written as a self-contained document intended for the day-to-day user. It includes detailed specification of the use of the above results in both design and analysis. Examples of both are included.

The procedure is presented in both analytic and nomographic forms in Appendix E. The key nomographs are those affecting the equations in Table 8. These are shown in Figure 11. There are also some computational aids based on Figure 10.

A Package Program for the Procedure

Appendix F contains detailed information on a package program developed by the researchers to effect the computations involved. The appendix includes a listing of the FORTRAN IV source.

The program handles both design and analysis problems, ramp weave, and major weave. It includes a feature by which consecutive analysis problems can be done without intermediate headings, so that comparison is simplified. Another feature allows one to step through a range of weaving volumes, designing for an appropriate length for each. In this way, one can plot and/or note required length as a function of weaving volume, all other parameters being fixed.

Discussion of Design and Operation

A number of points of concern to the designer that should be considered in the context of the recommended procedures and techniques are discussed.

Differences in speed exist between the two weaving flows. The speed S_w found or specified is the composite of the two. The heavier volume weaving flow is the faster of the two. This pattern is much more pronounced for ramp weaves than for major weaves.

It must be remembered that true weaving sections—in the sense of both physical weaving configuration and two significant weaving movements—are not as common as is often thought. Frequently only one weaving flow exists and the problem is really one of merge and diverge. This is handled by the procedures of HCM Chapter 8. For those true weaving sections of the ramp-weave type, it is questionable practice to make them longer than 2,000 ft. For true major weaves, the equations can be used under caution that they are not so precise in this region.

The nomographs can be used for the longer situations by simply extending the *L* scale for major weaves, which is linear. A nomograph extension is shown in Figure 11 (B) (dashed line).

The question of when a weaving section appears to be a normal freeway section has been of recurring interest to designers. Intuitively, one might expect that this would tend to occur as the section was made longer. The HCM considered such an out-of-the-realm-of-weaving regime. In the present work, it was found that such a regime existed only under certain conditions. It is referred to herein as effective nonweaving.

Two ways of viewing the problem are from (1) comparable speeds, or (2) comparable service volumes. The former can frequently be resolved, as indicated in the illustrative problems and the equations. The latter—as determined by a net service volume approaching $SV = V_{TOT}/N$ —cannot be achieved in ramp weaves and cannot generally be attained in major weaves.

While one may question whether this result may be attributed to the limitations of the calibration, it must be remembered as cited earlier that (1) the merge and diverge turbulence will always exist, regardless of length, and (2) there is intensive lane changing at the beginning of the section because of the intensive presegregation, adding to/causing the turbulence. In the case of ramp weaves, there is the added fact that there is rarely the ramp-to-ramp volume to use much of the auxiliary lane space at the activity level implied by such an *SV*.

It should be noted that a typical weaving section is subjected to a range of flow conditions. Depending upon the season, or even the time of day, the relative magnitudes of flows may differ, sometimes significantly. The weaving section may have to be designed with several flow patterns in mind. If it is not, the operation under some of these patterns possibly may appear to be poor simply because the section was designed for only one specific set of conditions.

It may also happen that the type of driver using a given weaving section is sometimes radically different from the drivers using the sections on which the calibration data for this procedure were collected. The composite data base generally reflects peak-period drivers for certain levels (the poorer levels of service were generally recorded then) and weekdays off-peak drivers at others (the better levels). The impacts of recreational driving populations, to the extent that they differ from these populations, have not been ascertained. Proper advance signing and other practices can aid in avoiding pathological problems that could arise by substantial lack of the presegregation that has been observed as characteristic of weaving sections.

On the subject of shifting flow patterns, it may happen that a design pattern has shifted significantly and somewhat permanently. It may be possible to modify the section lane arrangement—including number of lanes on each leg—with markings rather than with physical reconstruction.

It should be noted that two-sided weaves (sections in which one of the weaving flows is the largest flow and/or virtually the mainline flow) are routinely handled by the major weave classification. Two-sided weaves are just a special flow pattern with a high *VR*.

Multiple weaves are more complex, and guidelines and discussion are given in Appendix I.

A last point: the lanes required for each nonweaving (outer) flow can be computed individually. One may then ensure that sufficient width exists on the two respective sides of the weaving activity. This, as a rule, is handled by

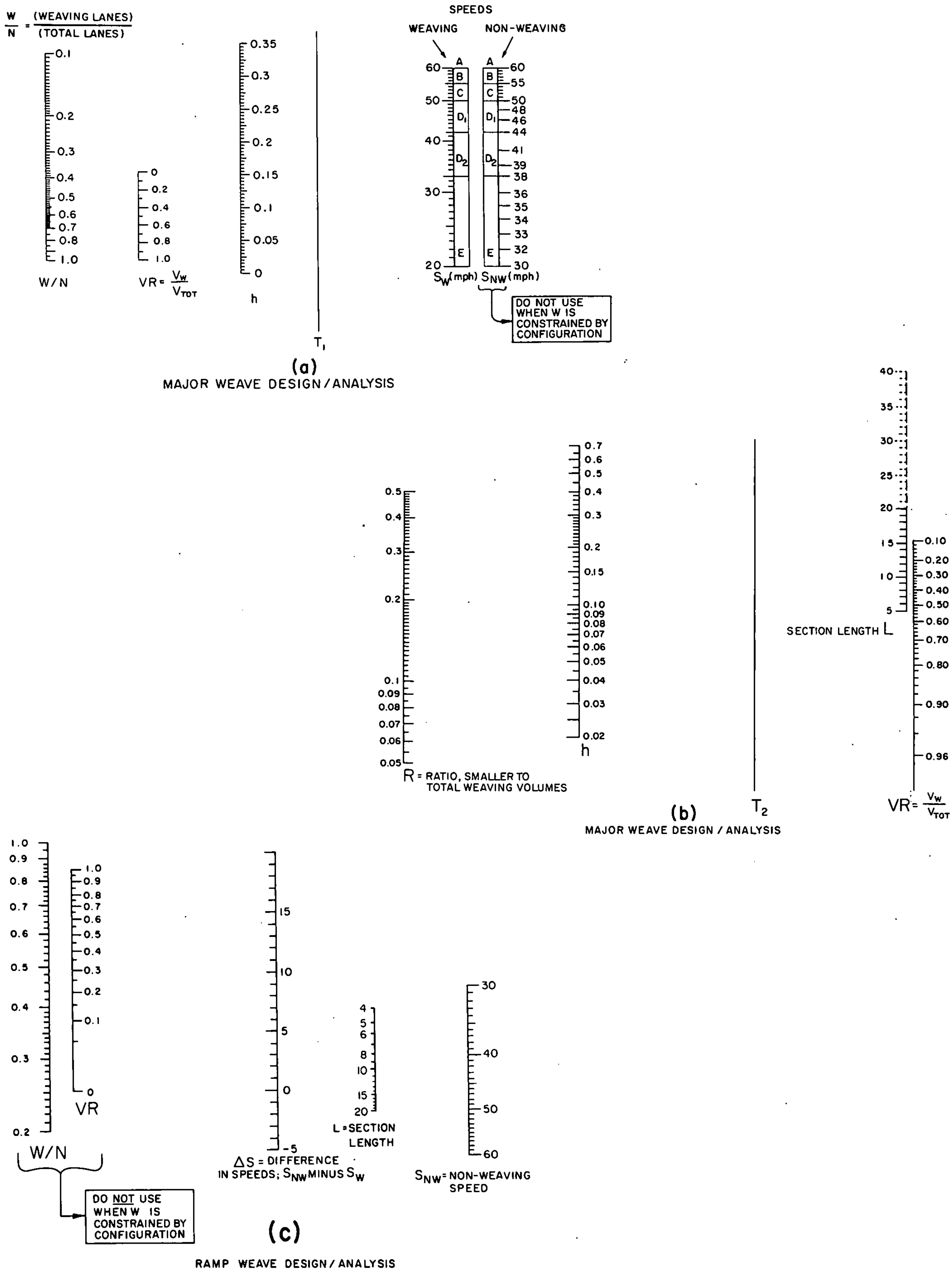

Figure 11. Three key nomographs used in design and analysis of weaving sections.

checking the adequacy of the lanes on each leg. In situations where the design is marginal or the designer desires reinforcement or further insight, he may wish to compute the nonweaving lane allocation on each side of the section.

APPLICATIONS OF THE RECOMMENDED PROCEDURE

This report contains a number of examples, both actual and postulated cases, worked by means of the recommended procedure. Appendices E and F contain examples illustrating the detailed procedural steps and the computer program, respectively. Appendix D contains analyses of data from the project data base that were withheld from the calibration either because of special features or expressly for this data check. Appendix D also contains an analysis of the data collected on the Gowanus Expressway earlier in the project.*

Appendix G contains an analysis of the Ward-Fairmount weaving section (*7*). Although the HCM procedure was not able to properly assess the problem existing at this site, the recommended procedure was able to do so.

In the course of the review of the user-oriented document (Appendix E), the Massachusetts Department of Public Works applied the procedure for the analysis of an existing situation (Central Artery Bridge over the Charles River, Boston) and were well satisfied with the results.

MECHANISMS OF WEAVING: RESULTS

The project data base was used for a wide range of microscopic studies, and a number of microscopic models for various purposes were formulated. These investigations served two purposes: (1) they were a guide and a control in the macroscopic investigations, and (2) they provide in and of themselves a better understanding of the basic mechanisms of weaving section operation.

This section summarizes the results of these investigations. Further details are contained in appendices when appropriate.

In regard to the weaving mechanism and procedure, these studies affirm and/or reaffirm several points.

- There is very substantial presegregation of the weaving and nonweaving traffic as it enters the weaving section. The degree of presegregation lessens as section length increases, but the sensitivity is significant (under 2,000 ft) for ramp weaves.

This result supports the macroscopic formulation, which identifies lane use as a later sequence of nonweaving-weaving-nonweaving allocations, with interaction built into the procedure via the weaving percentage *VR*. It also indicates one of the basic mechanisms wherein length does have an effect—the input distribution is not as acute for longer sections, particularly in the ramp-weave situation.

This result also implies that there is a substantial upstream (and downstream) influence of the weaving section because drivers must pre-sort and then unsort themselves. Lacking specific data for those regions, this effect may be estimated using lane-changing matrices with selected values (*8*).

- Configuration is indeed an important factor. The importance of configuration is shown in the lane-changing model of Appendix C and in the linear programming model of Appendix H.
- The benefit of increasing length dissipates rapidly. This is also demonstrated in the two models cited, although the illustration in Appendix H is somewhat extreme because of the specific values employed in the example.
- Weaving sections are often controlled (as regards level of service provided) by specific concentrations of vehicles or "hot spots" within the weaving section. Conversely, some areas within the weaving section are underutilized.

This characteristic is found throughout the investigations. The lane-changing model (App. C) implies this because the highly skewed input distributions *—combined with lane-changing probabilities are invariant with longitudinal distance—lead to a concentration of lane changes at the beginning of the section. The linear programming model (App. H) very graphically shows that a number of internal points frequently become saturated before the length limitation, as such, comes into effect. The net effect, as regards macroscopic models based on field data that have this characteristic intrinsically, is that the importance of length is less than it would be otherwise. The Gowanus Expressway data (Appendix XVI †) show the cited characteristic in an actual field situation, as does the project data base.

- As far as can be discerned, the lane-changing probabilities are not dependent on volume, longitudinal position within the weaving section, or section length. They do vary according to essential or nonessential lane changing, and—for nonessential changes—according to the direction of movement.

These results confirm the assumptions essential to lane changing and linear programming models, which are presented.

- A weaving section may be, and frequently is, subjected to a wide range of conditions as regards flow levels and combinations thereof. This range can occur within a typical day, a few hours, or over seasons.

Table 10 gives the range of flow conditions for one experiment from the project data base for which the levels of service as computed from the recommended procedure are also indicated. It is of importance that the designer appreciate that such ranges exist and that more than one set of values may have to be considered in doing his evaluation.

- In addition to very substantial presegregation, the multiple weave site in the project data base also gave evidence that the proportional allocation of weaving recommended in the HCM (weaving allocated in proportion to subsection lengths) does not hold.

This finding, based on the microscopic data of this one experiment, is detailed in Appendix I. A discussion on the

* These data were collected in the first part of the project by aerial photography both to obtain data on a long (4,080 ft) section and to assess the collection technique itself. As a matter of record, this effort is summarized in Appendix XVI (not included in this publication; see Appendix J herein for additional information).

* The skew is accentuated by the presegregation on each leg, but is not due solely to it When vehicles enter the section, they are limited initially to those internal lanes that correspond to the lanes on their input leg.

† Not included in this publication. See Appendix J herein for additional information.

TABLE 10

RANGE OF FLOW CONDITIONS IN PROJECT EXPERIMENT 12; CROSS-WESTCHESTER EXPRESSWAY, WHITE PLAINS, NY

	RANGE OF FLOW (PCPH) FOR MOVEMENT [b]				LEVEL OF SERVICE (ANALYSIS OUTPUT, RECOMMENDED PROCEDURE)	
TIME [a]	1	2	3	4	NON-WEAVING	WEAVING
2:02PM	1506	123	642	284	B	D
08	1670	140	440	310	B	D
14	1530	170	500	390	B	D
20	1750	80	400	280	B	D
26	1840	130	340	340	B	D
3:41 PM	1960	91	747	485	B	D
47	1818	232	717	444	B	D
53	2731	269	634	516	C	D
4:14 PM	2443	247	691	454	C	D
20	2660	190	870	530	C	D
26	2828	333	980	808	D	E
32	3350	310	1070	630	E	E

[a] 6-min periods.
[b] As delineated in Fig. 1.

extension of the recommended procedure to multiple weaves, including an analysis of this and the four BPR data base multiple weaves, is also contained therein.

In addition to these findings and analyses, the researchers also established that:

- The *difference in speed* between the two weaving movements is such that the heavier volume is almost always the faster. This pattern is more pronounced for ramp weaves than for major weaves.
- While the accident rate is greater in weaving sections than on open freeway sections, it is not possible to attribute this rate specifically to length, weaving volume, or any other factor with the data at hand. In addition to the limited quantity of data, the researchers believe that other factors—signing, approach roadway, etc.—can be predominant and that an investigation should take all of these into account.

The following section presents details of these findings where appropriate.

MECHANISMS OF WEAVING: ANALYSIS

This section does not address certain developments that are treated extensively elsewhere in the report and that are already placed in context, such as the lane-changing and linear programming models.

Presegregation

One phenomenon noted in reviewing the project data base was the high degree of presegregation of vehicles entering the weaving section. That is, drivers on leg A destined for leg Y, in the main, had moved over to the curb lane of the mainline at some point in advance of the weaving section. This active presegregation on the part of users simplifies to the maximum extent possible the weaving process they must undertake.

Eleven experiments from the project data base were used to examine the magnitude of presegregation. These included both ramp-weave and major weave configurations and encompassed a range of section lengths from slightly over 500 to 2,000 ft. Of particular interest was how leg A traffic destined for leg X or leg Y aligned itself at the entrance to the weaving section. Table 11 presents the percentage distribution of the leg A traffic exiting leg Y (i.e., weaving traffic) and the traffic continuing on leg X (i.e., nonweaving traffic).

Weaving Traffic

Regardless of the number of leg A lanes or their section lengths, more than half of the exiting traffic is already in the curb lane of leg A at the entrance to the weaving section. If only ramp-weave configurations are considered, the data show that of the exiting traffic 69 to almost 98 percent has already moved into the curb lane prior to entering the weaving section. As one might expect, the shorter the section the greater the percentage of exiting traffic placing itself in the best possible position to make its necessary weave.

A similar pattern is observed in the major weave sections as well. Here, however, a greater percentage of vehicles is found to remain in the lane next to the curb lane than occurs in the ramp-weave sections. This may be due to the fact that, for most of the major weaves, leg Y had two lanes, which allowed relatively free movement for exiting vehicles from both the curb lane and the lane adjacent to it.

Through Traffic

Those vehicles entering the section and which desire to continue on along the main line tend to presegregate themselves in a manner opposite to that of exiting traffic. That is, the majority of through traffic is found to be in lanes other than the curb lane. In the case of ramp-weave sections, 60 to 85 percent of through traffic has already positioned itself such that it will not be involved with weaving traffic.

A similar pattern is observed in the major weave sections. Here again, the configurational conditions of the multiple weaving sections affect the behavior of the users in different ways.

Summary Comments

In considering all the available data, users *do* align themselves prior to entering the weaving section in such a manner as to maximize the ease with which they traverse the section. Exiting motorists "move over" in large numbers to the curb lane, while through traffic tends to do just the opposite. Thus, the collective decisions of weaving section users result in significant presegregation.

TABLE 11

PERCENTAGE DISTRIBUTION OF LEG A WEAVING AND NONWEAVING TRAFFIC ENTERING THE WEAVING SECTION

NO. OF LEG A (EN-TRANCE) LANES	SECTION LENGTH (FT)	DISTRIBUTION (%) BY DESTINATION OF TRAFFIC ARRIVING ON LEG A							
		1[a]		2		3		4	
		EXIT LEG Y	CON-TINUE LEG X	EXIT LEG Y	CON-TINUE LEG X	EXIT LEG Y	CON-TINUE LEG X	EXIT LEG Y	CON-TINUE LEG X
(a) RAMP WEAVE									
2	750	2.6	79.0	97.4	21.0	—	—	—	—
	1200	7.5	60.2	92.5	39.8	—	—	—	—
	1467	22.5	77.4	76.6	22.6	—	—	—	—
3	750	0	41.8	2.5	43.3	97.5	14.9	—	—
	968	1.3	41.3	17.1	38.7	81.6	20.0	—	—
	2000	5.9	40.5	25.2	44.6	68.9	15.6	—	—
(b) MAJOR WEAVE									
2	527	6.6	56.6	93.4	43.4	—	—	—	—
	950	5.1	57.7	94.9	42.3	—	—	—	—
	1481	18.7	73.5	81.3	26.5	—	—	—	—
3	900	6.1	57.8	40.8	39.4	53.1	2.7	—	—
4	1355	0.1	20.2	2.6	49.4	26.1	29.1	71.2	1.3

[a] Entrance lane 1 is the median lane.

Upstream and Downstream Effects

Neither the BPR nor the project data base includes information on movements outside of the weaving section proper. The extent of weaving segregation indicates, however, that significant upstream and downstream effects must exist as a result of the vehicles presorting and unsorting.

In order to illustrate the possible magnitude of these effects, a typical role of project experiment 5 (Cross-Bronx Expressway eastbound over the Alexander Hamilton Bridge, New York City, N.Y.) was selected and is shown in Figure 12. Transition probabilities were chosen from (1) sample lane-changing probabilities extracted from Reference 8, and (2) probabilities comparable to the nonessential * lane change rates observed within the weaving section. The values are shown in Table 12.

* That is, a lane change made by a weaving vehicle within the section proper but not essential to complete the vehicle's weave.

Figures 13 and 14 show a summary of the effects for Reference 8 values and intense values, respectively. For the former values, there is a very mild shifting to and from the weaving segregation pattern such that the effect has impact—albeit mild—at least a mile away in both directions. For the latter values, the effects are more localized, being felt no more than 500 ft in either direction in terms of lane distributions and 1,000 ft in terms of sorting among lanes (e.g., Fig. 14 (B)). This, however, triples the area of influence of the 950-ft weaving section.

One may argue that upstream sorting is relevant but downstream unsorting by movement is not. Vehicles approaching the section are indistinguishably intermingled but

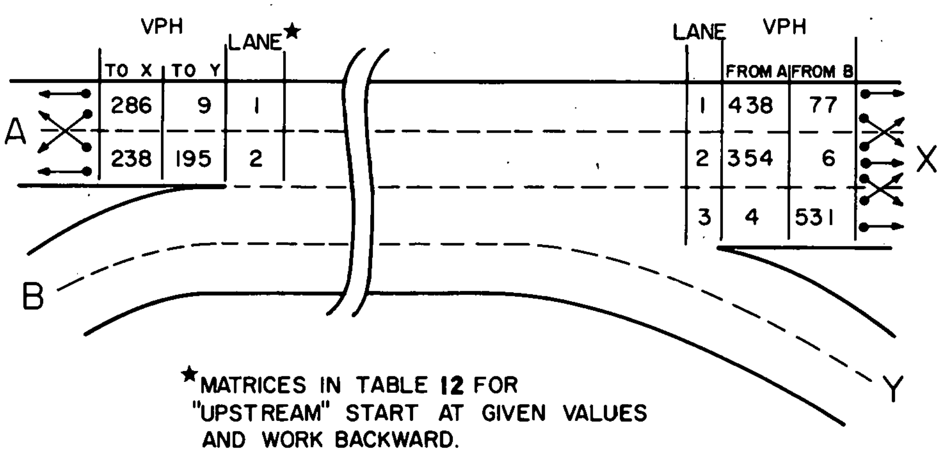

Figure 12. Estimation of probable effects upstream and downstream of a weaving section.

must presort according to purpose; having completed their purpose, it is only the total lane volumes that must redistribute to a balanced condition because the vehicles no longer have a distinguishing purpose. If so, the (b) parts of Figures 13 and 14 are not relevant. The magnitude of such effects would hold, however, for three-lane approaches.

The subject of upstream and downstream effects is discussed further in Chapter Four in the context of "Suggestions for Future Research."

Concentrations Within Weaving Sections

Figure 15 illustrates the concentrations within sections found in the project data base. Vehicles are counted twice when they change lanes—in the lane they change from and in the lane they change to, in the quadrant of the change. This highlights the impact of the change but does not distort the patterns unduly for the point now being made.

Concentrations such as these, observed in the actual data, are also predicted in the linear programming model of Appendix H. In that context, they are results of the drivers optimizing the volume-handling capability of the section within certain confines. The prime confine is invariant lane-changing probabilities, which account and/or allow for the propensity of drivers to concentrate lane changes at the beginning of the section.

Lane-Changing Probabilities

A lane-changing probability $p_{ij}(r)$ is computed by taking the number of lane changes from lane i to lane j in quadrant r and dividing by the total volume within the quadrant in lane i. Probabilities are computed separately for movements 1, 2, 3, and 4. To reduce the variability induced by consideration of short-term 6-min flows, consecutive 6-min data periods were aggregated to form 12-min flows. Further, periods with total lane flows (in the lane from which the lane change is made) of less than 20 were eliminated.

A distinction was found to exist as to essential versus nonessential lane changes. Note that for movement 2 of project experiment 5 (Fig. 16 (A)) lane changes from lanes 1 and 2 are essential if a vehicle in either of those lanes is to complete a weaving maneuver. Beyond that, however, a weaving vehicle may make a further change from lane 3 to lane 4. This lane change is not required to complete a weaving maneuver.

Data were analyzed for project experiments 2, 5, and 7. Values of $P_{ij}(r)$ were computed and plotted against several volume variables to investigate relationships between volume factors and $p_{ij}(r)$. Data were stratified by quadrants and examined. The relationships exhibited all lead to an invariant value for p. This lack of trend is shown for project experiment 5 in Figure 16 (B). This particular experiment is especially interesting for investigating the values of p_{ij} because the segment length ($L = 950$ ft/4) is quite close to the unit length of 250 ft adopted by Worrall.

Analysis of the three experiments cited revealed that (1) no trend with volume or quadrant could be discerned; (2) there is a difference between essential and nonessential lane-changing probabilities; (3) there is no discernible difference for essential lane-changing probabilities between the two weaving movements;* (4) there *is* a difference between nonessential probabilities for the two weaving movements; (5) there are no discernible differences with length for the two lengths available (either 750 or 950 ft), considering probability per unit length. Analysis of variance or regression analysis was used, as appropriate; conclusions were drawn at a significance level of 0.05. The results are indicative but not neecssarily conclusive (e.g., the length invariance). A summary of some of the resultant probabilities is given in Table 13.

* The variance of the data was sufficiently high that the limited sample may have precluded resolving a difference that seems to exist. Refer to Table 13.

Multiple Weave Mechanisms

Multiple weave sections are generally treated in the HCM as a sequence of subsections or segments for the purposes of analysis and/or design. Each segment is considered

TABLE 12

ESTIMATES OF UPSTREAM AND DOWNSTREAM EFFECTS

FROM \ TO	1	2	3
	(a) Upstream, some Ref. 8 values		
1	0.9532	0.0468	—
2	0.0103	0.9897	—
	(b) Downstream, some Ref. 8 values		
1	0.9866	0.0134	0.0
2	0.0075	0.9860	0.0065
3	0.0	0.0290	0.9710
	(c) Upstream, intense values		
1	0.55	0.45	—
2	0.15	0.85	—
	(d) Downstream, intense values		
1	0.6004	0.3996	0.0
2	0.2509	0.5233	0.2258
3	0.0	0.3237	0.6763

TABLE 13

LANE-CHANGE PROBABILITIES [a]

PROJECT EXP. NO.	ESSENTIAL $MV=2$	ESSENTIAL $MV=3$	NONESSENTIAL $MV=2$	NONESSENTIAL $MV=3$
2	0.57	0.46	—	—
5	0.64	0.40	0.29	0.16
7	—	0.46	—	—
All three	0.59 [b]	0.43 [b, c]	0.29	0.16
Final aggregation	0.52 [d]		0.29	0.16

[a] Probabilities based on 10 points or fewer not shown.
[b] The difference of 0.16 (0.59-0.43) for essential lane changes is not significant due, perhaps, to large variance of data.
[c] 0.46, if normalized to ~ 250-ft section.
[d] 0.53, if normalized to ~ 250-ft section.

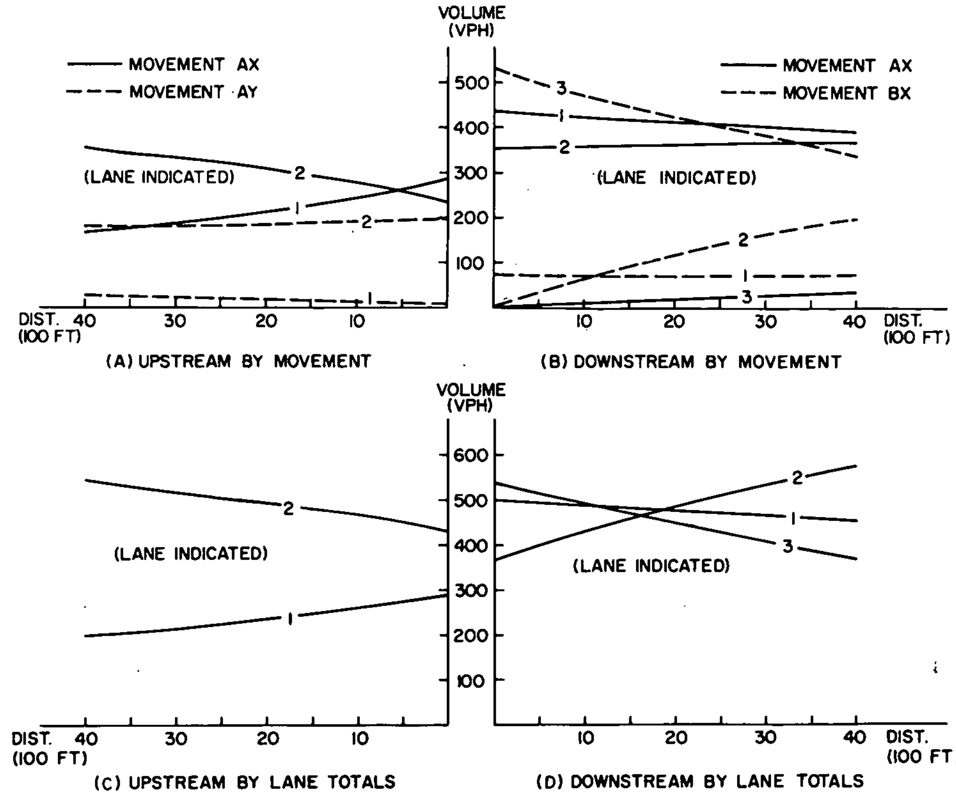

Figure 13. Diagrams of upstream and downstream effects for the estimated values given in (*a*) *and* (*b*) *of Table 12.*

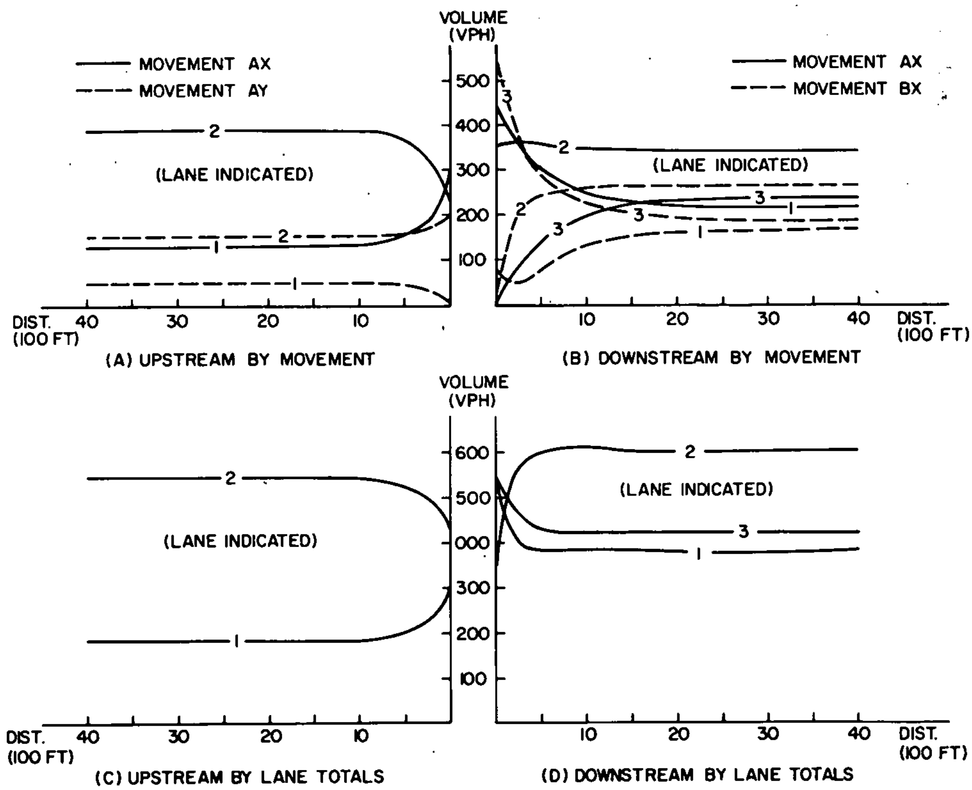

Figure 14. Diagrams of upstream and downstream effects for the estimated values given in (*c*) *and* (*d*) *of Table 12.*

separately in terms of its length and width requirements. The major problem in the HCM multiple weave design analysis is how to consider those weaving vehicles that traverse more than one segment. The position at which these vehicles execute their weaving maneuvers will affect the over-all design analysis results. The HCM recommends allocation of the weaving in proportion to the segment lengths.

One multiple weave section was collected as part of the project data base, the multiple weaves in the BPR data base not being amenable to a study of section-by-section mechanisms. Appendix I details the analysis of the data on two levels, that is (1) evaluation of the allocation hypothesis, and (2) guidelines for using the recommended procedure on multiple weaves.

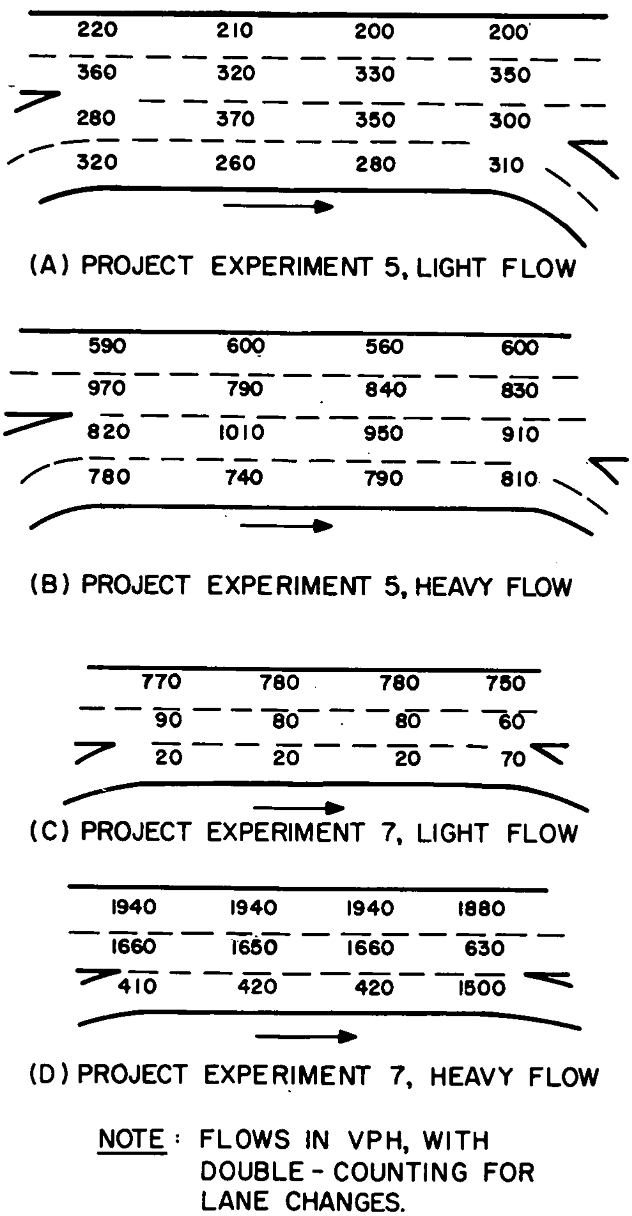

Figure 15. Examples of vehicle concentrations within weaving sections from project data base information.

Figure 17 shows the placement of slightly more than 3,900 vehicles entering the section during one roll of filming. The figure indicates the lane placement of vehicles at the end of segment 1 and at the middle and end of segment 2 by leg and lane of entry. Percentage distributions are also shown. In this case, at least, there was absolutely no "proportional allocation" of weaving between the two weaving segments. All the weaving maneuvers associated with the second exit were undertaken in the second segment.

Although the data are very limited, the fact remains that the practicing engineer will have to cope with the design and analysis of multiple weave sections. It is therefore necessary that guidelines be developed out of the existing knowledge to the maximal extent possible and that the engineer be advised to use them with appropriate caution.

After consideration of these points and investigation of the available experiments, the following guidelines are recommended:

1. Sketch the movements with consideration for pre-segregation and necessity to weave so that the location of weaves (and thus nonweaving and weaving volumes per subsection) are identified.
2. Classify the subsections as major weave or ramp-weave type.
3. Execute design or analysis as appropriate, subsection by subsection.
4. Review the over-all situation to determine if there are any limiting conditions. For analysis, poor performance in a downstream subsection may control an upstream subsection. In design, lengths may have to be varied or width may have to be changed. In design, the subsection widths must be compatible and should provide lane continuity (Appendix C).

The available project and BPR multiple weaves are reviewed in Appendix I according to these guidelines. Some insight and command of the recommended procedure is necessary.

Note that the guidelines recommend allocating each weaving flow to a single subsection, to be determined as previously discussed. Pending further research, this is the most appropriate recommendation.

Speed Differences Between Weaving Flows

A tendency of the greater weaving volume to also be the faster was observed in the course of the research. This is quite reasonable because the smaller volume must compete with the larger. Table 14 summarizes an analysis of the project data base in contingency table form. It was determined that there is a definite interaction at a statistically significant level of 0.05.

Inspection of these data indicates that the tendency is much stronger for major weaves than for ramp weaves. Again, this is logical because the configuration of a ramp weave is more of an equalizer in the data base than that of the major weave, which generally favors one movement by lane arrangement.

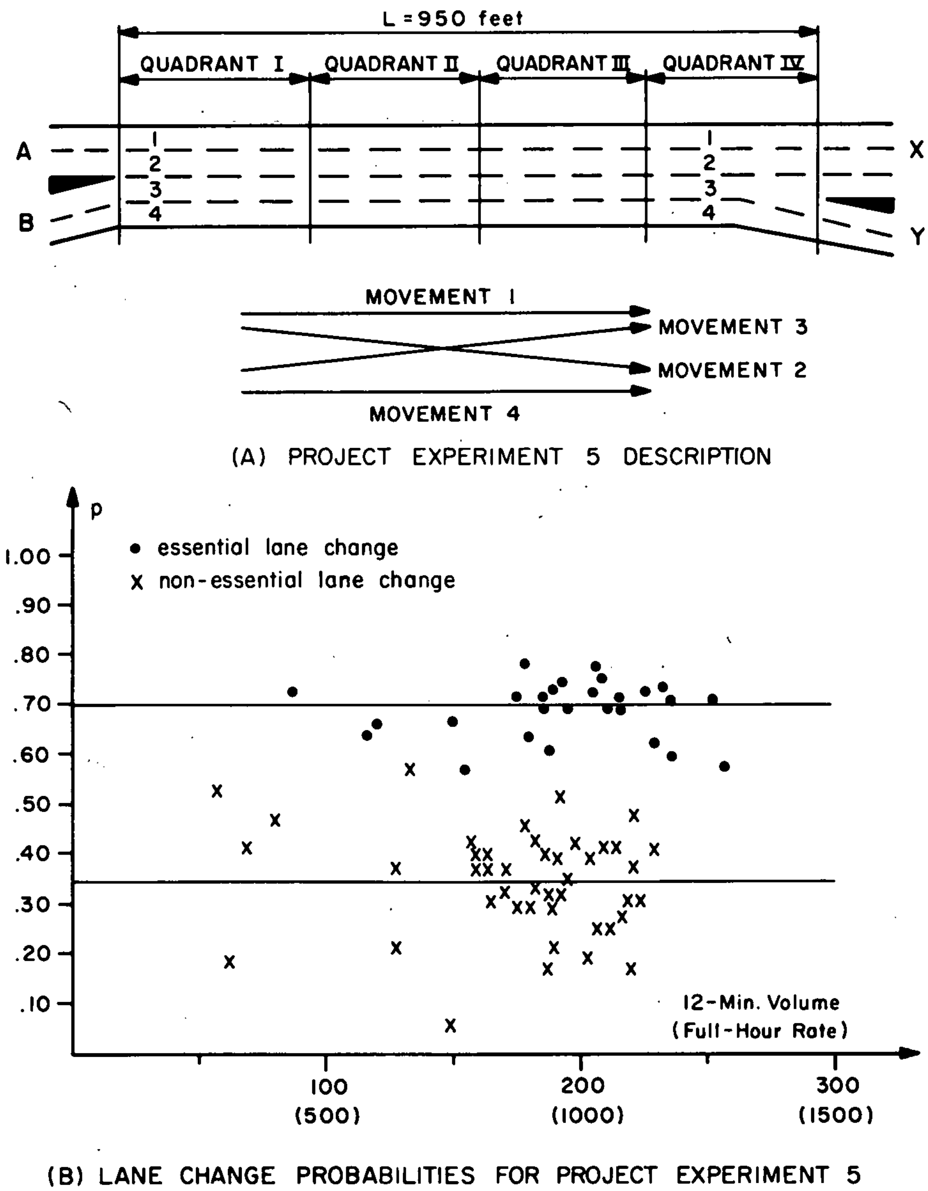

Figure 16. Diagram of lane-changing probabilities.

Safety Studies of Weaving Areas

A number of studies have attempted to relate the accident characteristics of weaving areas to both the intensity of weaving and the length of weaving area. The most notable of these, by Cirillo (*9*), included over 700 weaving sections and concluded that accident rates per 100 million weaving vehicles decreased as the length of the weaving section increased. The decrease was especially significant where weaving volumes were high.

As part of the data collection effort, the research agency also collected accident data for twelve of the study sites, each for twelve consecutive months between 1969 and 1970.

A total of 111 accidents occurred in the twelve study sites over a 12-month period, 77 percent of which were rear-end and sideswipe collisions. This is reasonable to expect because merging, diverging, and deceleration movements predominate in weaving areas. The majority of the remaining accidents were with fixed objects, predominantly in gore areas. Table 15 summarizes the accident data for the experiments considered.

Due to the relatively small number of accidents, accident rates per million vehicle-miles (MVM) and per million weaving vehicles for both total and sideswipe/rear-end accidents were related to weaving characteristics. Severity rates and other measures were not deemed appropriate because of the sample size. Weaving characteristics were investigated in terms of the percent of total volume which weaves (V_w/V_{TOT}) and the number of weaving vehicles per 1,000 ft of weaving section length (V_w/1,000 ft). Figures 18 and 19 show two relationships typical of those examined.

As the percent of weaving vehicles increases for ramp

TABLE 14

DIFFERENCES IN SPEED [a] BETWEEN WEAVING FLOWS

	$V_2 > V_3$		$V_2 < V_3$		TOTAL		DIFFERENCE	
	MAJOR	RAMP	MAJOR	RAMP	MAJOR	RAMP	MAJOR	RAMP
$S_2 > S_3$	7	102	2	70	9	172	$X^2\,0.05 = 3.84$	$X^2\,0.05 = 3.84$
$S_2 < S_3$	0	27	91	43	91	70	$X^2 = 7.77$	$X^2 = 64.6$
Total	7	129	93	113	100	242	—	—

[a] S_i is speed of movement i; V_i is volume of movement i.

weaves, the accident rate also rises. For other types of weaving sections, the relationship shows no strong trend. The relationship of accident rates to weaving intensity is similarly not strongly trended. This latter result does not confirm the trend observed in previous studies that longer weaving sections produce lower accident rates.

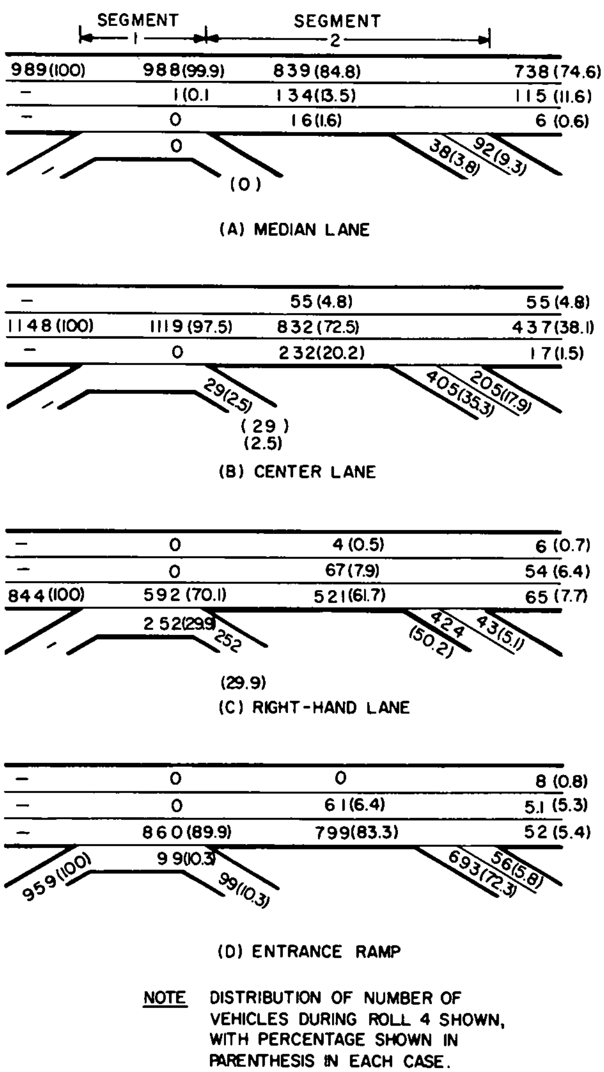

Figure 17. Placement of vehicles in multiple weave section according to their entrance lane positions.

The small size of the data base utilized herein makes any definitive statement concerning these results impossible. The number of operational and physical factors that can affect the safety of a weaving area would require research involving massive data collection and extensive modeling techniques.

RELATIONSHIP TO OTHER WORK

There have been no other studies on the immediate topic that have used a broad data base. However, several interesting studies have centered on related issues of concern in the operation of weaving areas.

Of particular utility herein were the work of Worrall, et al. (*8, 10*) on lane-changing matrices and the Ward-Fairmount study (*7*) of Systems Development Corporation. Both of these served to illustrate and substantiate the ideas on the effect of configuration developed herein. Later work on analytic models (*11, 12*) was also of interest.

Other studies dealing with related areas of merging, ramp flows, lane changing, and gap acceptance have also been conducted in recent years. One major study, conducted at UCLA (*13*), examined lane-changing characteristics in advance of a freeway ramp. A major portion of the project

TABLE 15

ACCIDENT RATES IN WEAVING AREAS

		ACCIDENTS/MVM [a]		
PROJECT EXP. NO.	ACCIDENTS/ YEAR	TOTAL	SIDESWIPE AND REAR-END ONLY	ACCIDENTS/ MILLION WEAVING VEHICLES
2	15	4.3	3.4	3.0
3	3	1.5	1.5	1.0
4	13	3.0	2.3	1.1
5	10	2.1	1.9	0.8
6	10	1.8	1.8	0.9
7	16	9.6	4.2	3.3
8	11	3.0	2.2	2.6
10	3	2.1	0.7	1.0
11	8	6.9	6.9	4.8
12	2	0.7	0.7	0.7
13	20	5.5	3.3	4.2
15	25	4.6	4.4	7.1

[a] Million vehicle-miles.

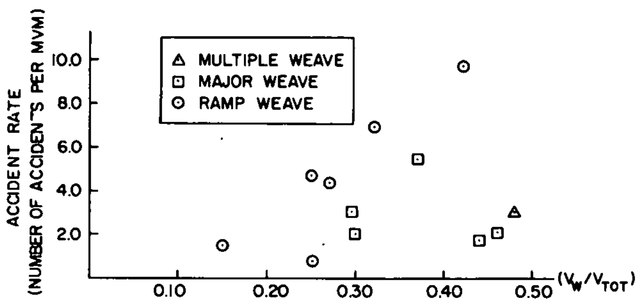

Figure 18. Plot of accident rate (per MVM) versus percent of weaving vehicles (V_w) *to total volume* (V_{TOT}).

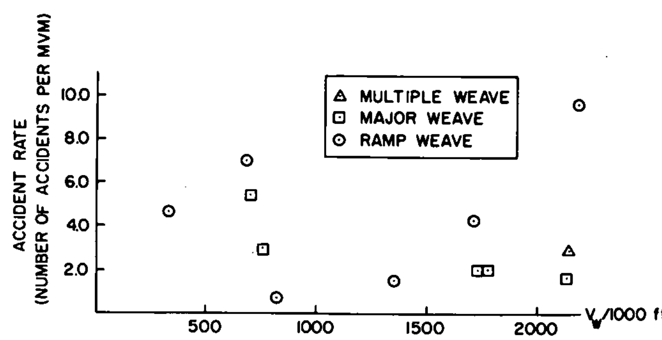

Figure 19. Plot of accident rate (per MVM) versus V_w *per 1,000 ft.*

was also devoted to the development of a complex data collection and reduction scheme that permits direct computer analysis and storage of individual vehicle trajectories. Although initially considered as a possible data collection mode for this project, its high cost eliminated it as a feasible method.

Gap acceptance and merging characteristics have been treated in the Worrall papers (*8, 10*) and others (*14, 15, 16*). These works are of interest but have only secondary bearing on this project.

The work of Cirillo (*9*) on weaving area safety provided background for a similar small-scale investigation of the same subject in conjunction with this project. Another study (*17*) of weaving safety was very microscopic but also very limited and had no ready applicability to the present undertaking.

Other work of peripheral interest includes the BioTechnology investigation of erratic movements in response to signing configurations (*18*). This data project did not have any applicability to the Weaving Area Operations Study in the context of the present study. Other papers of interest include a development of a work sheet for a three-segment multiple weave (*19*), a study of a restriping of a gore area on a California freeway (*20*), and the two relevant computer programs developed at ITTE (*4, 5*).

CHAPTER THREE

APPLICATIONS

This chapter summarizes the researchers' recommendations on the use of the project results and related considerations.

THE RECOMMENDED PROCEDURE

The procedure developed in this research and presented in Appendix E as a self-contained document is recommended for all major weave and ramp-weave design and analysis problems.

The recommended procedure should be used in lieu of the procedure of HCM Chapters 7 and 8 for the cases cited.

The computer program detailed in Appendix F is recommended as a computational aid, particularly in analysis problems.

For multiple weaves, the procedure developed herein is also recommended. It should be applied subject to the guidelines and cautions stated in Chapter Two and also in Appendix I.

AN OBSERVATION

Although the available data were limited to auxiliary lane cases, it was noted that lane 1 volume predictions were more accurate using HCM procedure 2 rather than HCM procedure 3, regardless of the level of service. Although data do not exist to generalize volumes for all ramp types, one becomes more cautious in the choice of which procedure to use for these other types in spite of the more appealing structure of HCM procedure 3.

SPECIAL APPLICATIONS

The HCM defines two special situations that are covered routinely in the recommended procedure. A two-sided weave, characterized by one of the weaving flows being the main flow of the section—usually with an appropriate configuration, is simply defined by a high $VR = V_w/V_{TOT}$.

A compound weave, said to exist when multiple lane changes are required by weaving vehicles, is characterized by a decreasing efficiency in volume-handling capability. This is reflected in the decreasing incremental benefits of added weaving width *W* in the recommended procedure.

Because the research did not extend to the analysis of metered inputs, which are coming into more common use, the following observation is appropriate. Note that two of the prime benefits of ramp metering are limitation of the input volume and introduction of greater uniformities in the entries. The recommended procedure can be used to assess the impact of various input volumes on section performance so that a decision can be made on what input volume should be permitted. In the case of very concentrated loads (such as arrive from a very nearby signal), the effective volume may be rather high for short periods; metering can alleviate this.

EXISTING PRACTICES

The researchers conducted a survey of current practices, which are summarized below and detailed in Appendix B. The AASHTO policies are also reviewed. Together they set the importance and context of a new procedure.

Current Practices

The researchers sent questionnaires on current practices in design and analysis of weaving sections to the fifty states and to thirty-five major consultants in December 1971. A total of fifty-one responses—thirty-eight states and thirteen consultants—was received. There are three major points to be made:

1. A difference of opinion exists regarding whether Chapter 7 or Chapter 8 of the HCM should be applied to weaving areas of the ramp-weave type. More use Chapter 7, despite the fact that the HCM recommends Chapter 8.
2. The HCM is used more for analysis than for design.
3. The HCM is used more than the AASHTO "Blue Book" for both analysis and design. (Note, however, that the HCM procedures herein were found to not be sufficiently accurate and/or well structured. Therefore the evaluation is important.)

AASHTO Policies

The AASHTO design policies have always utilized the HCM as a source for capacity determinations and have used the procedures therein for computation. Except for specifying design capacity at a given level of service, procedures are analogous to the HCM treatments.

Where weaving areas are concerned, however, an element is added. AASHTO, in the 1965 AASHO *Policy on Geometric Design of Rural Highways,* cited speed standards in terms of average running speed rather than operating speed as in the HCM. The numeric standards are the same. Average running speed, as defined by AASHTO, is equivalent to space mean speed used to develop the procedure presented herein. In recent drafts for a revised policy, however, AASHTO is apparently adapting its standards to operating speed to conform with the HCM.

Relating to The Recommended Procedure

The new procedure has been developed entirely with respect to space mean speed because this statistic is both a more precise and obtainable measure than operating speed. At lower levels of service the difference between the two is negligible and rarely exceeds 5 to 6 mph under any circumstances. Therefore, little difficulty should exist in relating the recommended methodology to AASHTO design standards. Because speed is an explicit factor in the procedure developed herein, new AASHTO design standards can be easily converted to speeds that can be used to enter the new procedure, if necessary.

CHAPTER FOUR

CONCLUSIONS AND SUGGESTIONS FOR FUTURE RESEARCH

The conclusions of this research were best summarized in the recommendations of Chapter Three and the end product is that a new procedure for weaving section design and analysis has been developed and is recommended for use. In the case of multiple weaves, it is recognized that the guidelines presented are based on limited data.

Specific suggestions for future research and comments that may be of use to other researchers are as follows:

1. *Data collection and reduction*—The researchers have had considerable experience with ground-based time-lapse photographic data collection. Although this is an extremely effective mode of collection, allowing both fine detail in the data extracted and an opportunity for later review not otherwise possible, several problem areas exist, which include (1) equipment, (2) vantage points and film details, and (3) cost of data reduction. The potential for equipment problems should not be underestimated. Time-lapse cameras apparently are not designed for the intensive use

typified by 5 hr of filming at two frames per second; the analyzers (projectors adapted for frame-by-frame sequencing) must be carefully chosen, for some may literally burn up because of such concentrated use; the analyzers may also be subjected to a lifetime's use in only a few months at that rated use. The researchers found substantial preventive maintenance essential for both cameras and analyzers, and the assistance of an in-house skilled technician was invaluable.

With regard to vantage points, the researchers found both agencies and owners of private properties to be extremely helpful. In spite of this, problems of camera angle, potential parallax, and sun position still had to be resolved. Film type had to be selected according to available light; angles had to be watched for glare and color wash-out; filters had to be considered.

Above all, the cost of reduction must be properly anticipated. The costs of reducing the data are greater than those of collection. Moreover, the reduction teams may have only 60 to 70 percent efficiency because they take regular periodic breaks which are essential to relieve them of the strain of the work. Experience has shown that the efficiency figure can rarely be bettered. Dead time due to equipment problems also contributes to reduced efficiency.

2. *Multiple weaves*—The guidelines developed for multiple weaves were not based solely on the one experiment in the project data base. The general results on segregation of flows supported the observations on the multiple weave, and the two reinforced each other. Still, it would be valuable and informative to obtain results on other multiple weave section(s). Should such data be collected in the future, it should include speed by subsection for each movement as well as volumes identified by input lane and subsequent lanes at each subsection end (for each input lane). In principle, this can be achieved by license plate identification.

3. *Methodology for improving precision of cases*—In the course of this research, a methodology was developed to determine which cases of HCM procedure 2 would benefit most from additional data. The methodology is presented in Appendix XV.* Although such ramp data were not collected in the current research, the results of the methodology may be useful to others. The methodology itself is recommended for application to other such situations.

4. *Transition model of freeways*—The lane-changing transition matrix formulation was of value in the work of Worrall, et al. (*4*), and in the present research. The linear programming formulation yielded practical concentration patterns while maximizing section productivity (i.e., volume) within the confines of a lane-changing structure. In principle, such a model can be structured for a general freeway section including on-ramps, off-ramps, and weaving sections. It is recommended that such a model be considered in a basic research effort, with emphasis on the data required to use it and the potential benefits of the understanding such an exploration could bring. The model should yield results comparable to observed empirical conditions, such as HCM procedure 2 lane 1 volumes, in appropriate test cases.

* Not included in this publication. See Appendix J herein for additional information.

5. *Safety characteristics of weaving sections*—The results of the accident analyses conducted in this research did not lead to a definitive dependence of accident rate on volume, section length, or other factors. Although the sample was rather small, which might be considered the reason for inconclusive results, there were more substantial reasons in the opinion of the researchers. First, accident rates are functionally dependent on volume rates existing at the time of occurrence, but the best volume data available—and this is generally true—are ADT figures. Second, the accident rates on file (yearly) may not correspond to such (V_w/V_{TOT}) values as observed in the field samples. Third, the effects of signing, geometrics, and delineation may well control. These impacts could not be considered systematically in the data at hand.

On the basis of this experience, the researchers recommend further research on weaving section safety characteristics that obtains data on accident occurrences, and volumes and (estimated) movement breakdown at the time of occurrence, and also support data such as ADT. A number of test sites should be selected so that length and signing effects (advance signing) can be isolated. In addition, relationships to required lane shifts (Appendix C) and to erratic movements (via microscopic modeling) may be considered.

6. *Adapting configuration*—In the course of the research, it was observed that the demand on a section may vary seasonally, and even within a given date. Certainly, the demand patterns on a section can grow and shift over a long period of time. Some applications—such as proximity to a road network improvement—can almost guarantee such changes.

Some localities use markings and lane striping to define and or redefine section configurations: lanes are dropped and added, lane continuity is established, and lanes per leg are adapted, all to suit current needs. Within the same physical area, the arrangements can be adjusted to suit different needs without major construction costs.

It is recommended that the advantages and operational experience with such techniques for flexibly adapting the physical plant be investigated, and recommendations and guidelines developed. Problems, such as abuses of delineated areas and (perhaps resultant) safety aspects, should be given special attention.

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APPENDIX A

LITERATURE REVIEW AND ANNOTATED BIBLIOGRAPHY

LITERATURE REVIEW

Early in the project, the literature was surveyed for all articles and papers concerning weaving and/or ramp operations. HRIS was utilized as well as independent reviews of major publication sources, including HRB special reports and records, NCHRP reports, and the journals *Traffic Engineering* and *Traffic Engineering and Control*. Some updates were done later in the project.

Articles treating both macroscopic and microscopic aspects of weaving, merging, and diverging traffic movements were inspected. Those articles of greatest applicability and relevance to the current effort are noted in the annotated bibliography.

ANNOTATED BIBLIOGRAPHY

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APPENDIX B

DETAILED RESPONSES TO CURRENT PRACTICES SURVEY

In December 1971, the research agency sent a questionnaire on practices currently used in design and analysis of weaving sections to the fifty states and thirty-five major consultants. A total of fifty-one responses—from thirty-eight states and thirteen consultants—was received. Because many of the consultants' replies indicated that they follow state practices, and there were few to the contrary, only those responses from the states are reported in detail.

This appendix contains a copy of the distributed questionnaire (Fig. B-1) and a compilation of the relevant responses.

COMPILATION OF RESPONSES TO QUESTIONNAIRE:

The responses are keyed by number to the items of the questionnaire. The figures in the compilation represent percent of responses unless otherwise indicated.

1(a-1) 70
(a-2) 24
(a-3) 6—Most frequent response considered them cases of merging and diverging

(b-1) 43
(b-2) 35
(b-3) 22—Most frequent response considered them cases of merging and diverging

2(a)	HCM Chap. 7	32	24	52
	Chap. 8	26	37	9
(b)	AASHO Design Manual	21	17	12
(c)	Own manual	9	7	9
(d)	Others	—	—	—
(e)	Comb. AASHO + HCM	12	15	18
	Total	100	100	100

3(a)	HCM Chap. 7	38	27	62
	Chap. 8	34	44	10
(b)	AASHO Design Manual	13	12	3
(c)	Own manual	4	5	6
(d)	Others	—	—	—
(e)	Comb. AASHO + HCM	11	12	19
	Total	100	100	100

4(a) 0
(b) 32
(c) 68
Total 100

5(a) 17 yes 83 no
(b) 54 yes 46 no

		NO. OF RESPONSES
(c)	Engineering judgment	5
	1000 ft desirable	4
	500 to 600 ft min	2
	700 ft min	1
	1600 ft min desired	1
	Depend on design speed	1
	Max. k limit = 2.95	1

(d) 38 yes 62 no

		NO. OF RESPONSES
(e)	Engineering judgments	6
	Table 7.3 as a minimum	1
	Lower k-values used for two-sided weaving	2
	Limit k-value	1

6. Of 38 states responding, California, Massachusetts, Pennsylvania, Texas, and Utah use own manual.

7(a) 81 satisfactory
(b) 19 unsatisfactory. Reasons:

		NO. OF RESPONSES
(7 and 8)	Configuration and ranges of application are limited.	1
(7 and 8)	More detailed user's instructions are desirable.	2
	Not satisfactory for arterial and undivided highway, c-d roads.	2
	Procedures are cumbersome and difficult to apply.	2

9(a), (b), (c) } 25 yes 75 no

Other General Comments on HCM:

	NO. OF RESPONSES
Users have no basis on which to confirm accuracy of the HCM.	7
Many HCM factors and criteria seem unrealistic.	8
Effect of number of lanes to be crossed should be considered in weaving.	1
More details on multiple weaving are desired.	4
Organization of the HCM seems poor.	3

NCHRP 3-15 "WEAVING AREA OPERATIONS STUDY"

QUESTIONNAIRE ON PRACTICES IN DESIGN & ANALYSIS OF WEAVING SECTIONS

Organization: ____________________

Person Completing Form: ____________________

Date: ____________________

1) Consideration of Weaving Configurations

a) ☐ Freeway ramp configurations (on-ramp followed by off-ramp), with auxiliary lane, are considered as a standard weave configuration.

☐ Freeway ramp configurations (on-ramp followed by off-ramp), with auxiliary lane, are considered as distinctly different from other weave configurations.

☐ Other (Please specify): ____________________

b) ☐ Freeway ramp configurations (on-ramp followed by off-ramp), without auxiliary lane, are considered as a standard weave configuration.

☐ Freeway ramp configurations (on-ramp followed by off-ramp), without auxiliary lane, are considered as distinctly different from other weave configurations.

☐ Other (Please specify): ____________________

5) Whichever of the above is used for design of weaving configurations, do you apply it without any modification or restriction?

☐ Yes ☐ No

If modifications or restrictions are imposed, do they include:

- Minimum length of a weaving section ☐ Yes ☐ No

  If YES, please explain and give minimum length: ____________________

- Relationship between Levels of Service and Quality of Flow given in Table 7-3 of the Capacity Manual ☐ Yes ☐ No

  If YES, please explain: ____________________

6) If you use your own manual, we may obtain a copy by:

☐ Enclosed with this response

☐ Requisition to ____________________

____________________ at a price of $________

☐ Unavailable

2) Which do you normally use in design of weaving configurations?

	Freeway Ramp W/Aux.	Freeway Ramp W/O Aux.	Other Weave
• Highway Capacity Manual			
Chapter 7 (Weaving)	☐	☐	☐
Chapter 8 (Ramps)	☐	☐	☐
• AASHO Design Manual (Blue Book or Red Book)	☐	☐	☐
• Own Manual	☐	☐	☐
• Others (Please specify) ____________________	☐	☐	☐

- Combination of ____________ and ____________

3) Which do you normally use in analysis of weaving configurations?

	Freeway Ramp W/Aux.	Freeway Ramp W/O Aux.	Other Weave
• Highway Capacity Manual			
Chapter 7 (Weaving)	☐	☐	☐
Chapter 8 (Ramps)	☐	☐	☐
• AASHO Design Manual (Blue Book or Red Book)	☐	☐	☐
• Own Manual	☐	☐	☐
• Others (Please specify) ____________________	☐	☐	☐

- Combination of ____________ and ____________

4) For what level of service is a weaving section designed?

Higher than thru section ☐

Lower than thru section ☐

Same as thru section ☐

7) Experience with the HCM has been:

☐ Satisfactory

☐ Unsatisfactory. Reason: ____________________

8) Experience with existing procedures (if not HCM) have been:

☐ Satisfactory

☐ Shown the following weaknesses:

1. ____________________
2. ____________________
3. ____________________

9) Do you use the ITTE capacity computer programs?

	Yes	No
Ramps	☐	☐
Weaving	☐	☐
Freeway	☐	☐

10) Whom do you suggest us to contact if we have any questions regarding this survey?

____

Figure B-1. Current practices survey questionnaire.

APPENDIX C

THE IMPORTANCE OF CONFIGURATION AND OF LANE BALANCE

Lane configuration is a factor that is not explicitly considered in the HCM weaving procedure. In the HCM computation for *N*, the total number of lanes required in the weaving section, no distinction is made between lanes required by weaving flows and lanes required by each outer flow. Yet, it is apparent that these lanes must be placed properly in respect to one another to adequately serve the traffic demand.

Lane configuration is a factor that has significant operational effects. This research shows that variations in lane configuration could influence the number of lane changes made in the act of weaving. The potential of lane configuration to limit component flows to the use of certain portions of the roadway would need to be treated specifically in a design/analysis methodology.

This appendix addresses the matter of configurational constraints in three ways:

- Rational development and confirmation from peak-hour data of the BPR data base.
- Further confirmation from the 18-min composite data base (which includes the project data base).
- Support by a lane-changing model.

The lane-changing model verifies that the lane arrangement (configuration) is important. This model, formulated to check this one aspect, lacks an internal capacity limit. Another formulation, presented in Appendix H, is more realistic in this respect. It too confirms that there is a configurational effect.

This appendix also addresses configuration/lane arrangement from the aspect of lane balance, which reinforces the previous analyses.

THE BASIC CONCEPT OF CONFIGURATION

Note from Figure C-1 (A) that all weaving movements in a ramp-weave section must take place in shoulder and auxiliary lanes. Secondary lane-changing movements are possible from the center lane. The extent to which the center lane may be utilized for secondary lane changing is primarily related to the length provided. With these considerations, it is seen that weaving vehicles could at best occupy in the order of two full lanes, assuming that the partial occupation of the center lane would be more than offset by the number of through vehicles using the shoulder lane as well as the inefficient use of the auxiliary lane itself.

It should be noted that the HCM Chapter 8 procedures indicate that even under heavy flows significant numbers of through vehicles will remain in the shoulder lane. Therefore, while it seems possible to have weaving vehicles occupy two full lanes, a reasonable maximum of one full lane plus a substantial proportion of a second might be a more appropriate assumption.

The major weave shown in Figure C-1 (B) is in many ways quite similar to a ramp-weave section. Weaving movements are again primarily restricted to two lanes, although secondary lane movements may take place from either of two outside lanes. Once again, it appears feasible for weaving vehicles to occupy two full lanes or somewhat more, depending on the extent of the outer flows. This geometry, however, can be slightly altered to produce a notable effect on possible lane utilization, as shown in Figure C-1 (C).

In this configuration, one weaving movement may take place without making a lane change. Weaving movements may be made with a single lane change (as is usually the case) from an additional two lanes. In the configuration of Figure C-1 (C), therefore, it is feasible to have weaving vehicles occupy three full lanes and possibly part of another. In addition, it would be expected that the weaving lane that requires no lane changes would serve weaving vehicles more efficiently than cases in which a weave requires a lane change.

Figure C-1 (D) presents a variation on (C) in that the "through weaving lane" may be available to either weaving flow. This might be of use when the section is subjected to different patterns, perhaps during AM and PM peaks.

These sketches indicate the potential power of lane configuration relative to the effective utilization of weaving section lanes and from the central concept of configuration.

The mere provision of the proper total number of lanes is not sufficient to guarantee the predicted operating characteristics. If one is not careful, lane arrangement may be such that the use of the lanes by weaving and nonweaving flows may not be in proportion to the relative flows, resulting in part of the roadway being underutilized while another portion is subject to breakdowns and forced flows.

Because lane arrangement depends on the design of entry and exit legs, it is important that any design procedure consider this element an integral part of the weaving area. In some cases it might be feasible to add lanes to exit or entry roadways, thus altering the over-all configuration rather than completely reconstructing a poorly operating weaving area.

USE OF THE BPR DATA BASE PEAK-HOUR DATA

The BPR data base can be used to substantiate the hypothesis of the effects of lane configuration on weaving area performance. Table C-1 gives the comparison between speeds of weaving and nonweaving vehicles for these data (peak hour). In most cases the speed of weaving vehicles and the speed of nonweaving vehicles are within 5 mph of each other. This is to be reasonably expected, as in many weaving situations weaving and nonweaving vehicles must

TABLE C-1

COMPARISON OF WEAVING AND NONWEAVING SPEEDS, VEHICLES IN BPR DATA BASE

SMS OF NONWEAVING VEHICLES COMPARED TO SMS OF WEAVING VEHICLES	NO. OF OBSERVATIONS: RAMP WEAVE	MAJOR WEAVE COLLECTOR-DISTRIBUTOR	ALL
>5 mph below	1	2	3
−5 to +5 mph	10	17	27
+5 to +10 mph	0	4	4
+10 to +15 mph	2	1	3
>15 mph above	4	0	4

share the same lanes and would have the effect of creating more or less uniform speeds throughout the section.

In some cases, however, there is enough roadway width to allow weaving and nonweaving flows to effectively be separated from each other. In such instances, the effect of weaving flows on nonweaving flows would be minimal, and large differences in speed might well be observed. As indicated in Table C-1, such differences most often occur on ramp-weave facilities with auxiliary lanes, where nonweaving vehicles may use the outer lanes. The geometry and lane configuration of a ramp-weave site restricts weaving vehicles to the shoulder and auxiliary lanes. On major weave facilities, weaving flows tend to be the dominant flows, and, with the provision of multilane entry and exit legs, weaving vehicles may occupy the major portion of the roadway. The higher speeds obtained by nonweaving vehicles in the ramp-weave case indicate that weaving flows might have expanded into the outer lanes had the lane configuration in the given length permitted it. In terms of balanced roadway space, such situations indicate an underutilization of outer lanes while congestion persists in weaving lanes.

In cases of wide speed differentials, elements other than segment length and volumes are restricting vehicles to certain portions of the roadway. The observable difference in speed characteristics for major weaves and ramp weaves suggests that configuration is the major restrictive element.

It is further possible to compute and estimate the number of lanes occupied by weaving vehicles by subtracting the number of lanes utilized by outer flows from the total number of lanes. The number of lanes (N) occupied by nonweaving vehicles (V_{01}, V_{02}) is taken as:

$$N_{01,02} = \frac{V_{01} + V_{02}}{SV}$$

in which the nonweaving service volume (SV) is generated by a straight-line interpolation between the speed and volume values given in HCM Table 9.1, based on the average speed of nonweaving vehicles. The results are given in Table C-2.

The results of Table C-2 bear out the hypothesis on lane configuration outlined and shown in Figure C-1. In no case do weaving vehicles occupy more than 2.0 lanes for ramp-

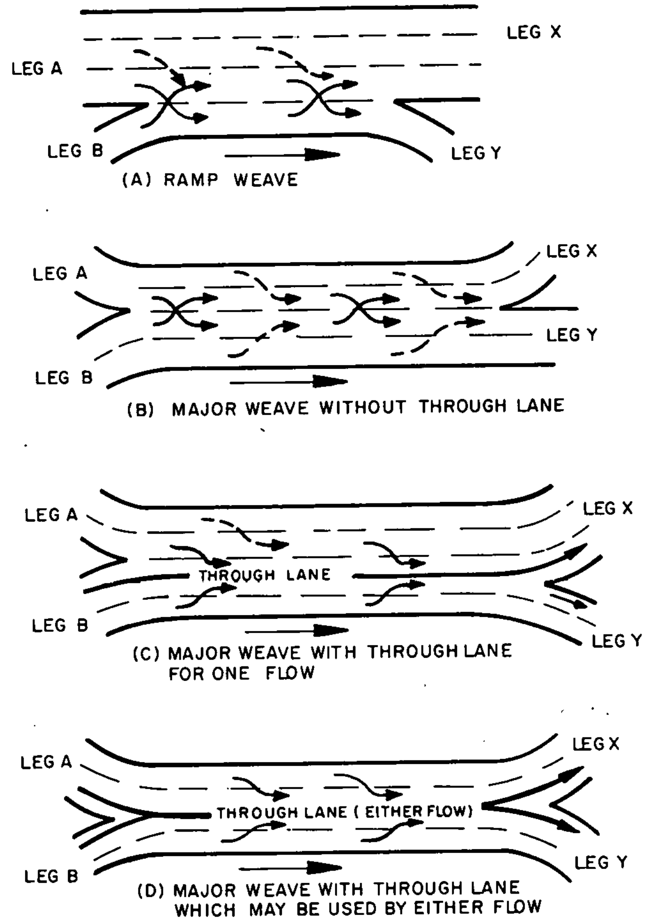


Figure C-1. Diagrams of ramp-weave and major weave sections.

weave sections (1.75 is the maximum observed). For major weaves, all but one case have weaving vehicles occupying more than 2.0 lanes; one case has weaving vehicles occupying 3.43 lanes. It should be noted that all of the major weaves in the data base are of the type depicted in Figure C-1 (C). The sample does not include any cases of the type shown in Figure C-1 (D).

Although it is true that the major weaving sections had higher weaving volumes which would be expected to occupy more roadway space, the data of Table C-2 give positive indication of the effect of configuration. The wide speed differentials observed for ramp-weave cases are a clear indication of unbalanced roadway utilization by the various component flows.

The BPR data and the analysis of lane configuration to this point permit a formulation of maximum lane utilization standards. These are given in Table C-3. This formulation is refined in the next section.

USE OF THE CALIBRATION DATA BASE

It was decided to use the calibration data base (composite data base, 18-min periods) to reaffirm the above analysis. This was done because the 18-min data base (1) would offer a greater range of cases (flow combinations) than the peak-hour BPR data alone, (2) was developed with a

TABLE C-2

NUMBER OF LANES OCCUPIED BY WEAVING AND NONWEAVING VEHICLES (FREEWAY CASES ONLY)

EXPERIMENT NO.	COL. 1 NONWEAVING VOLUME	COL. 2 WEAVING VOLUME	COL. 3 NONWEAVING *SV*	COL. 4 TOTAL LANES	COL. 5= COL. 1/ COL. 3 NONWEAVING LANES	COL. 6= COL. 4– COL. 5 WEAVING LANES
Ramp weaves:						
3	3986	1098	1765	4	2.25	1.75
7	3374	1666	1460	4	2.30	1.70
8	3157	1775	1265	4	2.49	1.51
9	4572	1526	1804	4	2.53	1.47
11	5008	1354	1485	5	3.54	0.55
12	5918	638	[a]	5	—	—
14	6222	627	[a]	5	—	—
16	5719	940	[a]	5	—	—
17	3897	1112	1302	4	2.97	1.03
18	2487	951	1085	4	2.45	1.55
21	4220	539	1582	4	2.65	1.35
28	5096	1366	1455	5	3.50	1.50
29	1806	1434	1480	3	1.33	1.67
30	2030	1108	[a]	3	—	—
32	3902	1300	[a]	4	—	—
33	6133	1252	1582	5	3.92	1.08
34	2706	1131	980	4	2.76	1.24
Major weaves:						
4	4649	2486	1840	4	2.53	1.47
13	4555	2974	[a]	5	—	—
23	3478	2502	1570	5	2.20	2.80
24	3019	2293	1420	5	2.12	2.88
49	2933	2166	[a]	4	—	—
50	2814	2238	[a]	4	—	—
51	1913	1678	1470	4	1.30	2.70
52	2182	2453	1508	4	1.45	2.55
53	792	1823	1400	4	0.57	3.43
54	631	1767	1425	3	0.44	2.56
60	2384	2859	1718	[b]	—	—
61	2170	1869	[a]	[b]	—	—
63	1598	2564	1620	3	0.97	2.03
64	3100	3014	[a]	[b]	—	—
65	2465	1651	1440	[b]	—	—

[a] Level of service F prevails, service volume variable.
[b] Not available.

TABLE C-3

MAXIMUM UTILIZATION FACTORS FROM ANALYSIS OF PEAK-HOUR DATA

CONFIGURATION	MAXIMUM NUMBER OF LANES OCCUPIED BY WEAVING VEHICLES: POSTULATED FROM CONFIGURATION	OBSERVED FROM BPR DATA
Ramp weave	2.00	1.75
Major weave with no weaving movements possible without a lane change	2.00+	—
Major weave with at least one weaving movement possible without a lane change	3.00+	3.43

slightly different *SV* interpolation than above,* and (3) incorporated more experiments and treated other than the peak hour. The 18-min data period was used rather than the 6- or 12-min period because it exhibited a better systematic relation, as evidenced in the calibration analyses of Appendix D. The 6-min data particularly might have contained transient values that would have been misleading.

An analysis similar to that of the previous section was conducted. The results are summarized in Table C-4.

It is interesting that somewhat higher values do result, particularly for ramp weaves. As is the case for the peak-hour data, there is no discernible trend with section length.

The fact that higher values do occur is attributed primarily to the greater range of flow combinations contained in the 18-min data. Table C-4 is the formulation of maxi-

* It interpolated travel times rather than speeds. This difference was a minor refinement.

mum lane utilization standards incorporated into the recommended procedure (Appendix E).

An observation to make is that, although the maximum weaving width for ramp weaves is properly taken as 2.3, it is generally not realized. The recommended procedure as presented in Appendix E was run on a wide range of cases as part of the research activity. These cases used both actual and fabricated but reasonable design-hour flows, or peak conditions, for analysis. The weaving widths that resulted had a maximum of the order of 1.7, consistent with the peak-hour observations. Only with less common (for hourly rates) flow combinations was the maximum of 2.3 realized.

This result indicates that the maximum should be as shown in Table C-4 for it can in fact be realized and at the same time demonstrated that (1) the fact that such values did not appear in the BPR data base is not unsettling and (2) values of weaving width above 1.7 to 2.0 will not commonly result from the recommended procedure.

A LANE-CHANGING MODEL

The effects of lane configuration on weaving area performance can be demonstrated by utilizing lane-changing probability matrices of the type used by Drew and by Worrall. As noted, this model does not include an internal capacity limit nor is it essential to the points being made herein. Another formulation, presented in Appendix H, is more realistic in this respect.

Framework

Consider a weaving section that can be divided into subsections of length l so that N subsections comprise the total length L. If one defines $p_{ij}(r)$ as the probability of changing from lane i to lane j commencing in subsection r (assumed to be commenced and completed in subsection r for simplicity), then one may establish a transition matrix $M(r)$

$$M(r) = \begin{bmatrix} p_{11}(r) & p_{13}(r) & \cdots & p_{1m}(r) \\ p_{21}(r) & \cdots & & \vdots \\ \vdots & \cdots & & \vdots \\ p_{m1}(r) & \cdots & & p_{mm}(r) \end{bmatrix} \quad \text{(C-1)}$$

Figure C-2 shows the interpretation of $p_{ij}(r)$.

The output distribution of vehicles β may be related to the input distribution α by

$$\beta = \alpha \prod_{r=1}^{N} M(r) \quad \text{(C-2)}$$

in which

$$\beta = [\beta_1\ \beta_2\ \ldots\ \beta_m]$$
$$\alpha = [\alpha_1\ \alpha_2\ \ldots\ \alpha_m]$$

and the subscripts are lane numbers.

A matrix $M(r)$ can be defined for each movement within a weaving section for the elements $p_{ij}(r)$ are determined by what the drivers wish to do, whether to weave, continue through, etc. Only the matrices associated with weaving vehicles are considered herein. It is assumed that these vehicles will continually move in the direction of their desired weave. That is, there will be no trajectories such as lane 3 to lane 4 and then over to lane 1 in Figure C-2.

It is also assumed that (1) there is a single lane-changing probability p for weaving-vehicle lane changes, and (2) no double lane changes (lane 3 to lane 1, for example) occur in any single subsection. The first assumption implies that there is no variation in p from subsection to subsection.

For the configuration of Figure C-2, the lane-changing matrices for movements BX and AY are given by

$$M_{BX} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ p & (1-p) & 0 & 0 \\ 0 & p & (1-p) & 0 \\ 0 & 0 & p & (1-p) \end{bmatrix} \quad \text{(C-3)}$$

$$M_{AY} = \begin{bmatrix} (1-p) & p & 0 & 0 \\ 0 & (1-p) & p & 0 \\ 0 & 0 & (1-p) & p \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \text{(C-4)}$$

With the vectors α and β as defined, note that

$$\left.\begin{aligned} \alpha_{BX} &= [0\quad 0\quad \alpha_3\quad \alpha_4] \\ \alpha_{AY} &= [\alpha_1\quad \alpha_2\quad 0\quad 0\,] \\ \beta &= [\beta_1\quad \beta_2\quad \beta_3\quad \beta_4] \end{aligned}\right\} \quad \text{(C-5)}$$

TABLE C-4

MAXIMUM WEAVING WIDTH W VARIES WITH CONFIGURATION

CONFIGURATION	WIDTH (LANES)
Ramp weave	2.3
Major weave with a crown line	2.6 to 2.7 [a]
Major weave with through lane on direction of greater weaving flow	3.6

[a] An estimate. The data base was deficient in these cases.

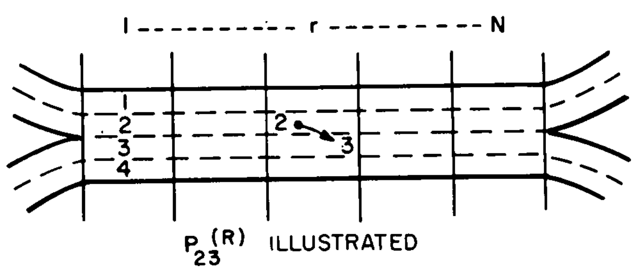


Figure C-2. Diagram of lane-changing probabilities.

where $\alpha_1 = \alpha_2 = 0$ for movement BX because entrance leg B does not impinge upon lanes 1 and 2. Similarly, $\alpha_3 = \alpha_4 = 0$ for movement AY.

The vector β includes the possibility of unsuccessful weaving movements. For example, for movement BX, $(\beta_1 + \beta_2)$ represents the "successful" weaves; that is, those which have completed lane changes into one of the lanes of their desired exit leg. $(\beta_3 + \beta_4)$ represents the "unsuccessful" weaves; that is, those which have not completed lane changes into their desired exit leg. The so-called "unsuccessful" weave will most likely force its way into the proper lane at the last moment, creating a serious traffic disturbance. It may be argued, therefore, that the number or percentage "successful" or "unforced" weaves is a good indicator of the quality of service being provided by a configuration.

The presentations herein illustrate the percentage of successful weaves as an indicator of quality. Appendix H contains a discussion of whether *percentage* or *number* is the more appropriate indicator. Percentage, however, is adequate for the points made herein.

A Case Study: Specification

The lane-changing matrices for the configuration of Figure C-3 (A) are now developed in detail, and those for the other configurations of Figure C-3 are also given herein. The distribution of vehicles at the output of each section is determined by the input distribution and by the probabilities $p_{ij}(r)$ that are assumed equal throughout the section.

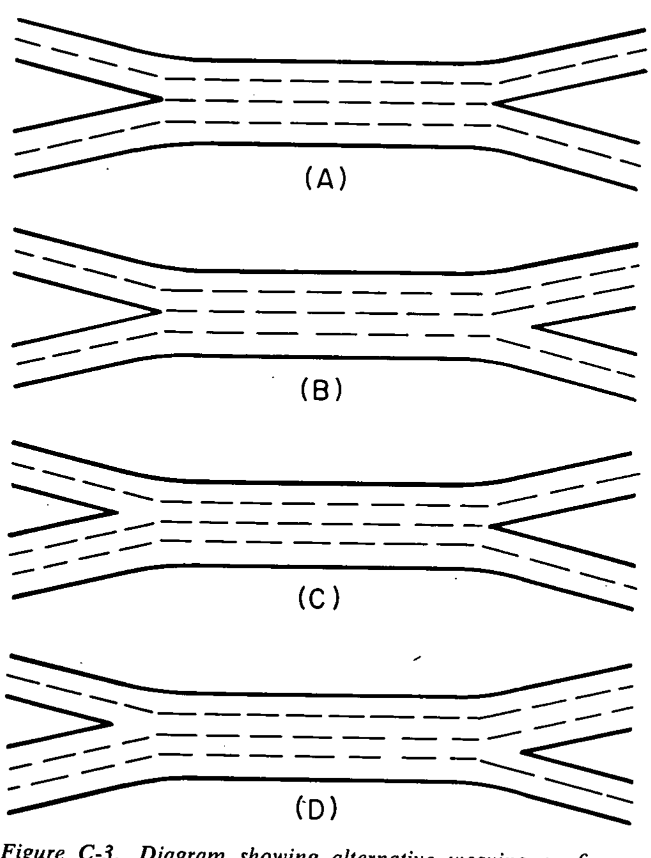


Figure C-3. Diagram showing alternative weaving configurations for a four-lane highway.

The four different configurations of Figure C-3 are compared for various probabilities p. Movement BX is taken to be of prime importance. Based on the various configurations and probabilities, only a certain number of vehicles have "successful" merges; that is, only a certain percentage is predicted to be in the proper exit lanes at the end of the section. This percentage P_{BX} is taken as an indicator of the quality of the section. Weaving vehicles not in the proper lanes would have to force their weave, thus degrading the section.

The following assumptions are made for simplicity in the illustration:

- Weaving vehicles entering on a given leg will be evenly distributed among the several lanes of that leg.
- The length is 1,500 ft; this is a typical length for such configurations.

The value of p is varied and comparisons are made.

In general for any of these configurations, the matrix $M^N{}_{BX}$ may be computed, and

$$[\beta_1\beta_2\beta_3\beta_4] = [\alpha_1\alpha_2\alpha_3\alpha_4] \begin{bmatrix} 1 & 0 & 0 & 0 \\ 1-(1-p)^N & (1-p)^N & 0 & 0 \\ R_1 & R_2 & (1-p)^N & 0 \\ R_3 & R_4 & Np(1-p)^{N-1} & (1-p)^N \end{bmatrix} \quad \text{(C-6)}$$

in which

$$R_1 = [1-(1-p)^N] - Np(1-p)^{N-1}$$
$$R_2 = Np(1-p)^{N-1}$$
$$R_3 = \left\{1 + (N-1)(1-p)^N - N(1-p)^{N-1} - \left[\frac{(N-1)N}{2}\right]p^2(1-p)^{N-2}\right\}$$
$$R_4 = \left[\frac{(N-1)N}{2}\right]p^2(1-p)^{N-2}$$

Having assumed for simplicity that entering vehicles are uniformly distributed across the available entering lanes, and defined P_{BX} as the probability of a *successful* weave, note that

For configuration A:

$$\alpha_{BX} = [0 \;\; 0 \;\; 0.5 \;\; 0.5]$$
$$\beta_{BX} = [\beta_1 \;\; \beta_2 \;\; \beta_2 \;\; \beta_4]$$
$$P_{BX} = (\beta_1 + \beta_2) \text{ or } 1 - (\beta_3 + \beta_4)$$

For configuration B:

$$\alpha_{BX} = [0 \;\; 0 \;\; 0.5 \;\; 0.5]$$
$$\beta_{BX} = [\beta_1 \;\; \beta_2 \;\; \beta_3 \;\; \beta_4]$$
$$P_{BX} = (\beta_1 + \beta_3) \text{ or } 1 - \beta_4$$

For configuration C:

$$\alpha_{BX} = [0 \;\; 0.33 \;\; 0.33 \;\; 0.33]$$
$$\beta_{BX} = [\beta_1 \;\; \beta_2 \;\; \beta_3 \;\; \beta_4]$$
$$P_{BX} = (\beta_1 + \beta_2) \text{ or } 1 - (\beta_3 + \beta_4)$$

For configuration D:

$$\alpha_{BX} = [0 \;\; 0.33 \;\; 0.33 \;\; 0.33]$$

$$\beta_{BX} = [\beta_1 \ \beta_2 \ \beta_3 \ \beta_4]$$
$$P_{BX} = (\beta_1 + \beta_2 + \beta_3) \text{ or } 1 - \beta_4$$

For the purpose of illustration, it has been assumed that movement BX is the major one, the one to be considered. Equation C-5 may be used with the above information to generate Table C-5. A weaving section length of 1,500 ft is assumed in generating Table C-5.

Results of the Case Study

Refer to Figure C-4, which summarizes P_{BX} for the range of p. For a given value of p, it is apparent that the most efficient configuration for movement BX is D, followed by B, C, and A in that order. This is not unexpected. Note that configuration D provides two lanes in which weaving movements may take place without a lane change, thus providing two "through" lanes for weaving vehicles. Both B and C provide one "through" lane for weaving vehicles, B by splitting a lane at the diverge, C by combining two into one at the merge. As the merging maneuver entails greater friction than the diverge maneuver, B would be expected to be more efficient. Because the analysis does not take this factor into account, the results are therefore a coincidence. Configuration A, which requires a lane change to be made for every weaving movement, is expectedly the least efficient.

These results reinforce the hypothesis on lane utilization presented previously. Configuration D will allow a larger portion of its width to be used by weaving vehicles than each of the other configurations, with B and C allowing greater utilization than A.

It should be noted that the four cases shown were selected to illustrate the effect of configuration. In terms of modern or recommended design, some of these are deficient. The analysis above indicates one of the prime reasons for this.

Sensitivity of Case Study Results

As both the length of the section and the lane distribution of entering vehicles were assumed, the results were also tested for their sensitivity to changes in these factors. The results of these sensitivity analyses are shown in Figures C-5 through C-7.

The sensitivity of P_{BX} to length is considerable, with longer lengths producing higher probabilities for successful weaves. The relative advantage of configuration D (the best) over configuration A (the worst) is greatest for the shortest length, an understandable indication that where lengths are more restrictive, configuration becomes a more vital design factor to consider. Conversely, shorter lengths may be possible in some weaving cases if the configuration is improved.

The sensitivity of P_{BX} to the lane distribution of entering vehicles is low for configuration A, a good deal higher for configuration D. This too is understandable, as in configuration A all weaving vehicles must execute at least one lane change, regardless of their lane of entry. A shift in the lane distribution in configuration D may substantially increase the number of weaving vehicles which do not have to make a lane change.

TABLE C-5

SOLUTION FOR P_{BX} FOR FOUR ALTERNATE WEAVING CONFIGURATIONS OF 1500 FT ($N=6$)

CONFIGURATION	P_{BX}
A	$1-(1\text{-}p)^6-0.5\,[6p\,(1\text{-}p)^5]$
B	$1-0.5\,(1\text{-}p)^6$
C	$1-0.66\,(1\text{-}p)^6-0.33\,[6p\,(1\text{-}p)^5]$
D	$1-0.33\,(1\text{-}p)^6$

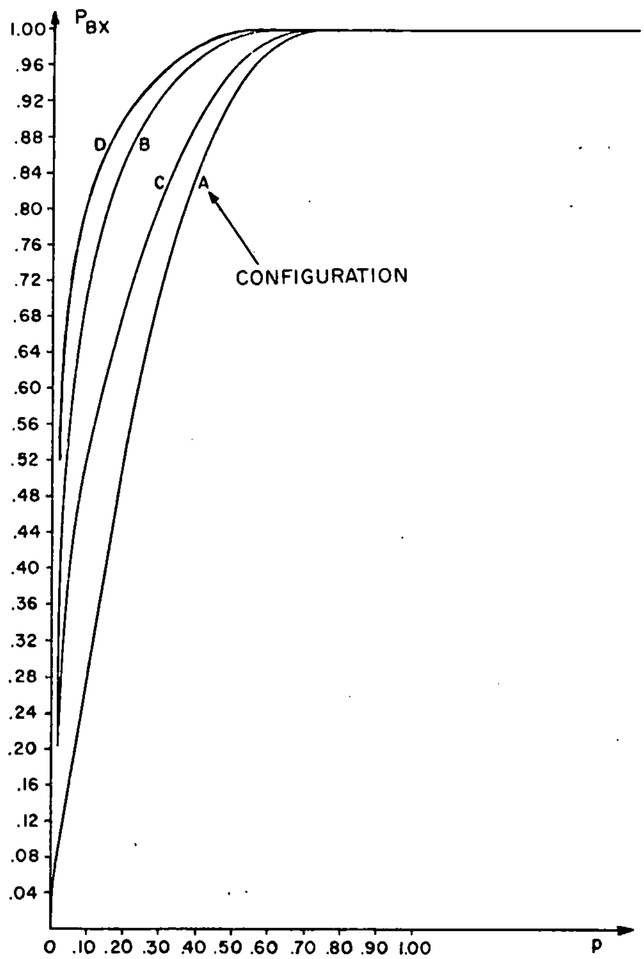


Figure C-4. Comparison of configuration efficiencies for various values of p *for the weaving movement BX.*

A Note on the Assumptions

The above analysis assumed (1) equal distribution of weaving vehicles on input legs, (2) lane-changing probability p invariant with position (longitudinal) in the weaving section, and (3) lane-changing probability p invariant with volumes.

It is shown in Chapter 2 of the report text that (1) the weaving traffic is strongly presegregated as it enters the section, (2) the probability p is dependent on neither length nor volume to any discernible degree, and (3) there is a difference between probability p_e of essential lane changes

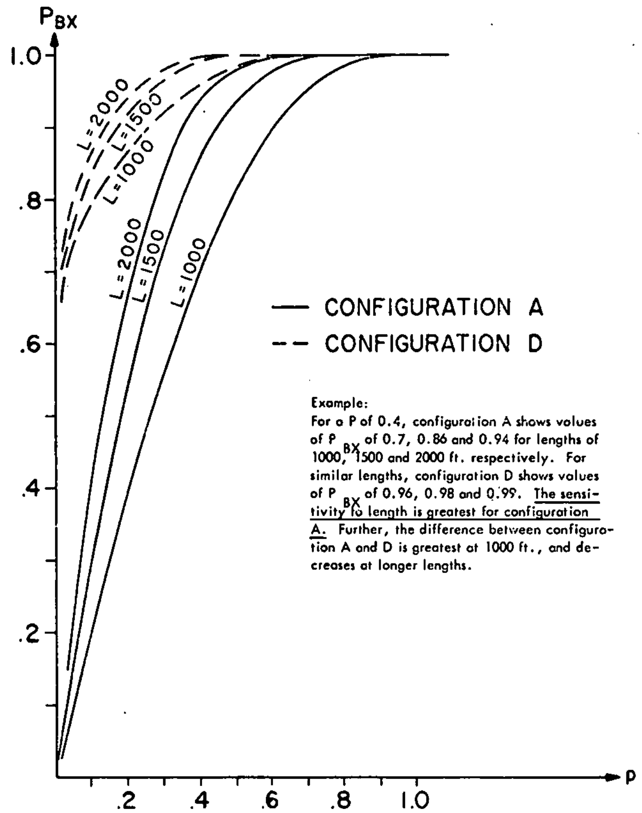


Figure C-5. Sensitivity of P_{BX} *to length as a function of* p.

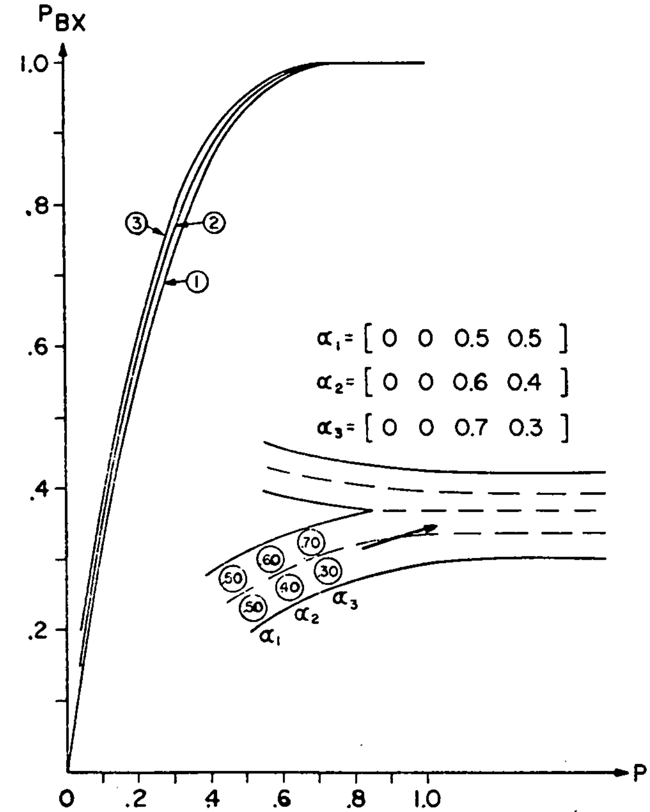


Figure C-6. Sensitivity of P_{BX} *to lane distribution for configuration A.*

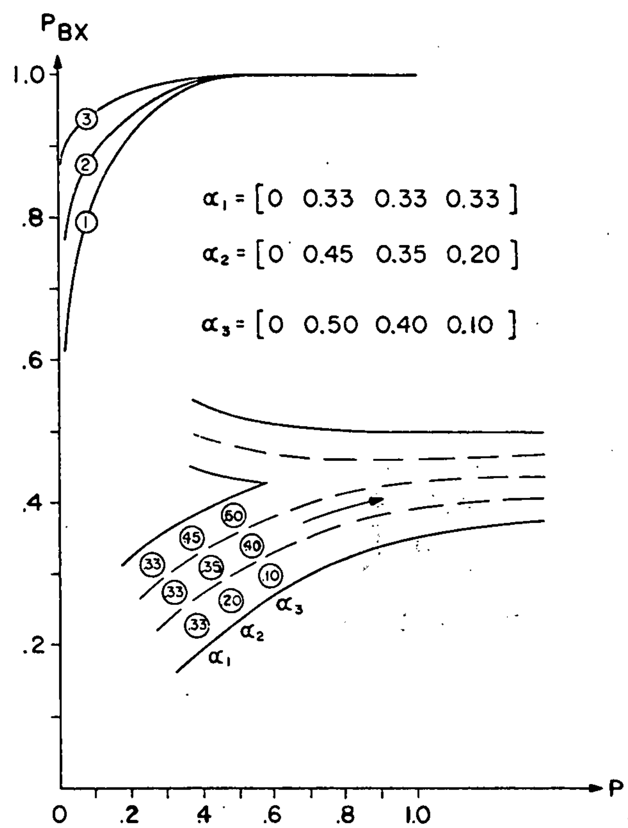


Figure C-7. Sensitivity of P_{BX} *to lane distribution for configuration D.*

and probability p_{ne} of nonessential lane changes.* The results are based on detailed analysis of experiments 2, 5, and 7 of the project data base.

These results have no negative effects on the above analyses because (1) the sensitivity analysis above addresses the impact of strong presegregation, as is in fact the true field condition, (2) the invariance of p with respect to length and volume is an important basic support of both the above analyses and the Appendix I work, and (3) the distinction between p_n and p_{ne} is not important above because p_{ne} influences only the distribution among "success" lanes.

A Note on Number of Lane Changes

It is a fact that substantial numbers of weaving vehicles choose to make their lane changes at the beginning of a weaving section. This is not at all inconsistent with the "invariant lane changing probability" result. Indeed, it is a natural outgrowth of such a statement.

Consider a lane with 100 vehicles and $p = 0.70$. In the first section seventy vehicles make the desired lane change. In the second section only thirty vehicles remain so that $30\,(0.7) = 21$ lane changes from the subject lane occur. Thus the *number* of lane changes is greater at the beginning of the section.

In Appendix E, the proclivity of drivers to effect sub-

* An essential lane change is one the driver *must* make to effect his weave; a nonessential lane change is one he *may* make.

stantial numbers of lane changes at the beginning of the section (a natural outgrowth of presegregation and invariant p) is cited as a probable cause for (1) the limited benefit of added section length after some initial increment, and (2) the lack of a steady convergence to an "out-of-the-realm-of-weaving" situation. Given the imbalance due to presegregation and the cited proclivity of drivers, there is always a certain turbulence at the beginning of the section.

LANE BALANCE AND LANE CONTINUITY

This section treats section configuration and lane arrangement from a different point of view. It emphasizes design to include a "choice" lane at the bifurcation and over-all design to minimize the number of lane shifts required of the weaving traffic. The analysis reinforces the concepts previously discussed and the weaving design and analysis procedure developed in this work.

Lane Balance

Lane balance is the arrangement of lanes at entrances and exits to provide for orderly, smooth, and efficient operation of traffic. It may be expressed by two simple statements:*

1. Entrances should be designed so that the number of lanes on the combined roadway beyond the merge should be not less than the sum of all the traffic lanes preceding the merge minus one; and not more than the sum of all the traffic lanes preceding the merge.

* Although expressed somewhat differently, it is essentially the same concept as presented on p. 489 of AASHO's *A Policy on Arterial Highways in Urban Areas* (1957).

2. Exits should be designed so that the number of lanes on the combined roadway in advance of the diverge should be equal to the sum of all the traffic lanes following the bifurcation minus one. In special cases with a single-lane exit (i.e., the common ramp weave) the number of lanes in advance of the diverge may be equal to the sum of all the traffic lanes following the bifurcation. In modern design, however, it has frequently been recommended that this form be avoided on full freeways.

The six basic cases of isolated entrances and exits in Figure C-8 comply with the lane balance principles outlined. One evident feature is that, with a two-lane entrance, a lane must always be added on the facility beyond the entrance. Also, with a two-lane exit, an extra lane on the freeway must always precede the ramp exit, and the same lane must be dropped on the freeway beyond the bifurcation. A further indication of the lane balance principle is that a traveled way having an exit should not be reduced by more than one traffic lane at a time. Another significant feature, excluding the special case under point 2, is that the lane balance principle applied to exits provides "one more lane going away" (i.e., the number of lanes on the individual roadways is one more than the number on the freeway before the bifurcation).

The one case not covered in Figure C-8 is a special situation of a two-lane entrance joining the freeway on two exclusive lanes. This form of entrance complies with the lane balance principle noted in the latter part of point 1.

By complying with the six cases of isolated ramps in Figure C-8, lane balance features are automatically provided for. The same features apply to weaving sections.

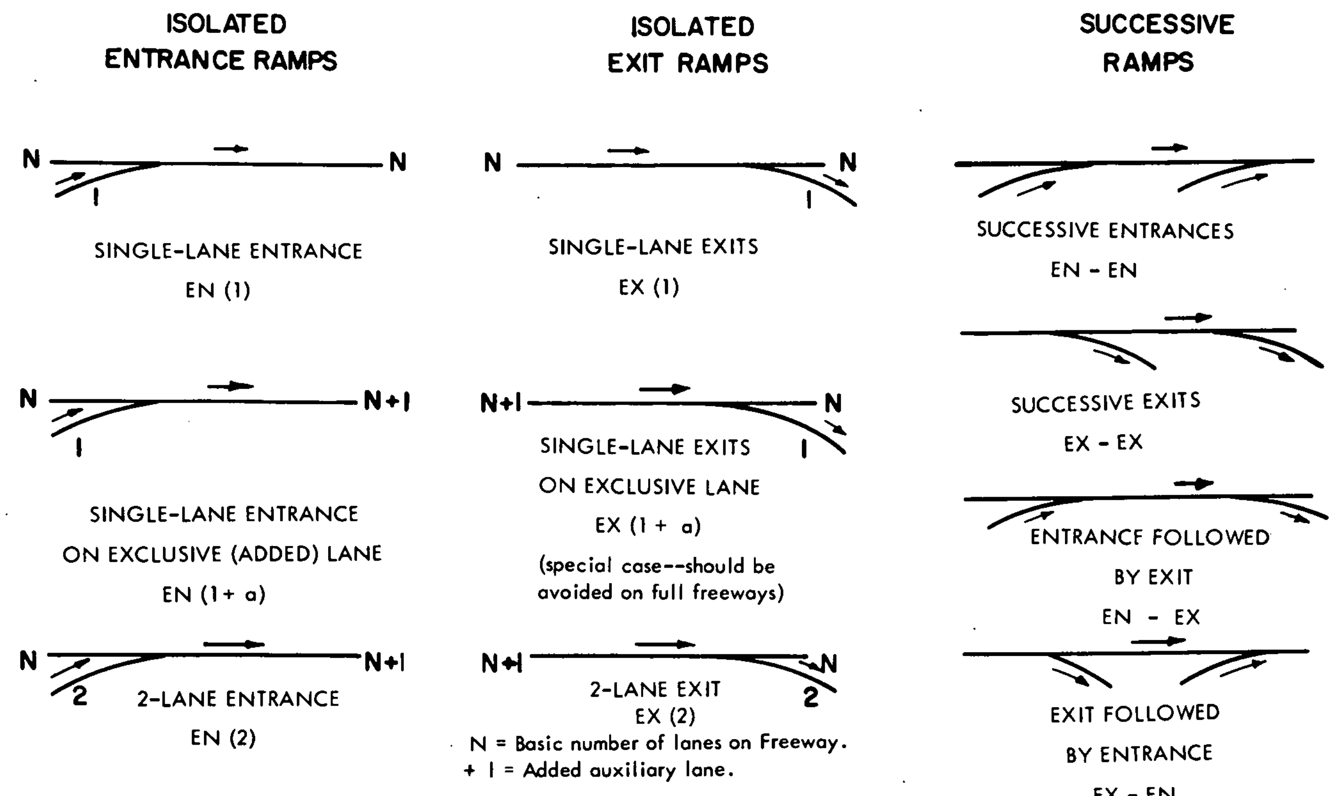


Figure C-8. Ramp cases for determining service volumes and capacities on freeway facilities.

The numerous combinations of entrance and exit terminals that can be utilized within a weaving section, coupled with different numbers of basic lanes on the freeway, produce a large variety of possible lane arrangements. Some of these are illustrated in Figure C-9. It is obvious that a weaving section of a given number of lanes can yield considerably different amounts of potential lane shifts. Arrangements that do not fully provide lane balance, particularly where the feature of "one more lane going away" is not present, may produce two and even three times the number of potential lane changes that occur on fully lane-balanced weaving sections. It can be seen that five of the basic isolated ramp cases (excluding EX 1) in Figure C-8 can be combined in various ways to produce weaving section designs with only two potential lane shifts. Figure C-9 shows examples in the three lower arrangements on the left and the two lower arrangements on the right.

It would appear that weaving sections with the larger number of lane shifts, even though the number of lanes within the section is the same and the weaving volume is identical, are apt to operate at a poorer level.

Lane Continuity

Lane continuity is another feature on freeways with ramps, particularly within weaving sections, which may have a significant effect on operation. Lane continuity refers to maintaining the basic number of lanes and keeping them continuous along a "designated" route. The designation may be by route number or name. Lane lines must conform accordingly and auxiliary lanes when added and removed likewise should be governed by the designated route. In studying weaving section operations and in establishing relationships and analysis procedures, this feature must be identified.

The two upper four-lane weaving sections in Figure C-9 apparently have the designated route running horizontally from leg A to leg X, in which case lane continuity is provided. On the other hand, if the designated route were to proceed from leg A to leg Y through each weaving section, there would be no route continuity. In the latter case less favorable operating characteristics would be evidenced where all through traffic must change lanes. However, should the route be designated from leg A to leg Y, the lane lines should be realigned to provide continuous movement. The entering and exiting traffic would then be subordinated to the through movement. Another example of poor lane continuity is where lanes, at exits and entrances, are dropped on one side and picked up on the other side of a through facility.

Lane arrangements with respect to lane continuity and lane balance, therefore, are significant features affecting operations with weaving sections.

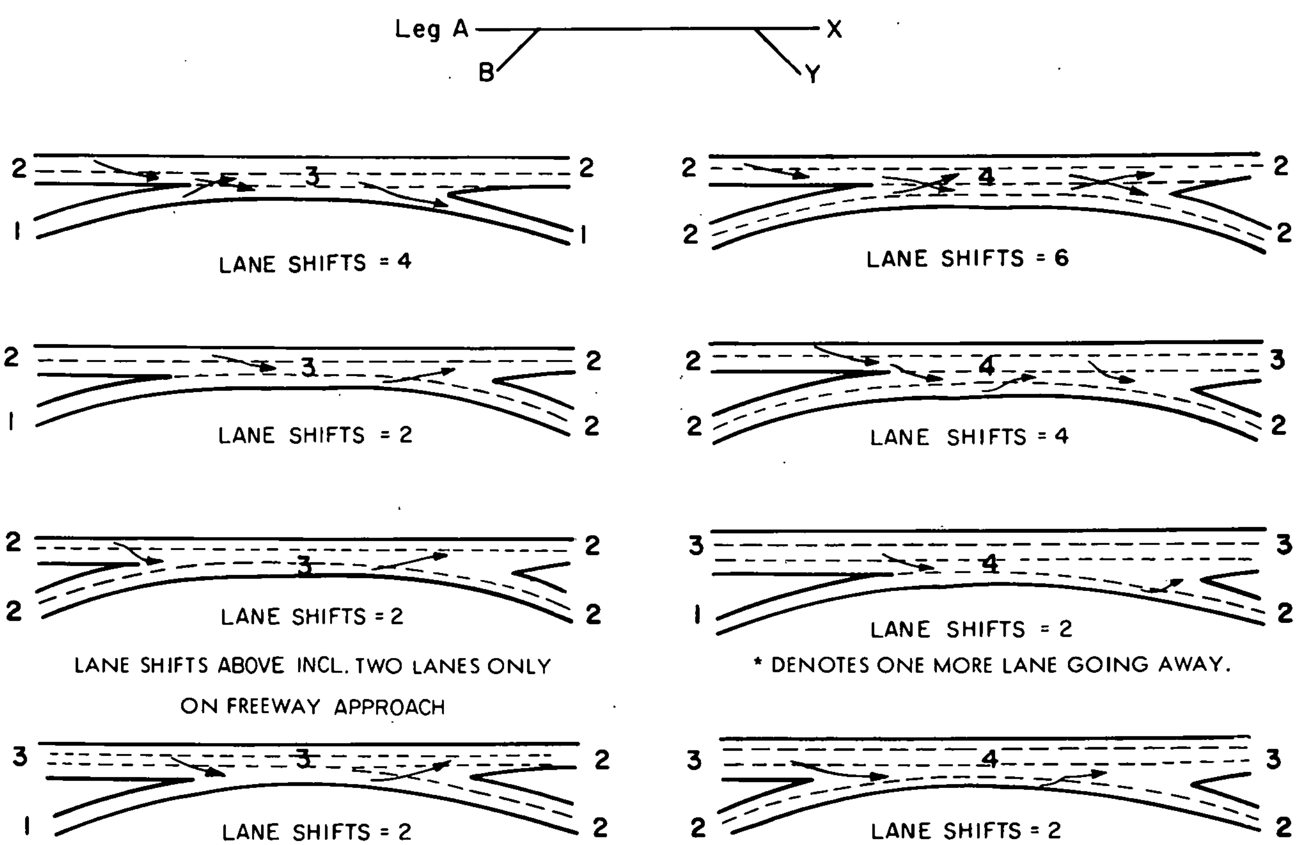


Figure C-9. Diagrams showing lane balance that provides operational flexibility and reduces lane changing.

Other Considerations

The above covers primarily right-hand entrance and exit situations. The right-hand ingress-egress arrangement is most prevalent and highly favored. It is anticipated that left-hand ramps will be gradually phased out on primary highways. However, at this time there is little information available for properly evaluating capacities and levels of service on left-hand ramps, and none to cause it to be discernible as a distinct case. There is a definite place for the left-hand ramp in conjunction with distribution-type facilities.

To illustrate the existence of such cases, the Dan Ryan Expressway (southern section) in Chicago and Highway 401 (freeway) in Toronto are examples with high-type continuous collector-distributor roads on which the transfer roads form left-hand ramps on the collector-distributor roads. Along these roads a variety of successive ramp arrangements present themselves with ramp junctions both on the left and on the right. Parallel to the four cases of successive ramps for right-hand situations covered in Figure C-8, the arrangements for various combinations of left-hand ramps are shown in Figure C-10.

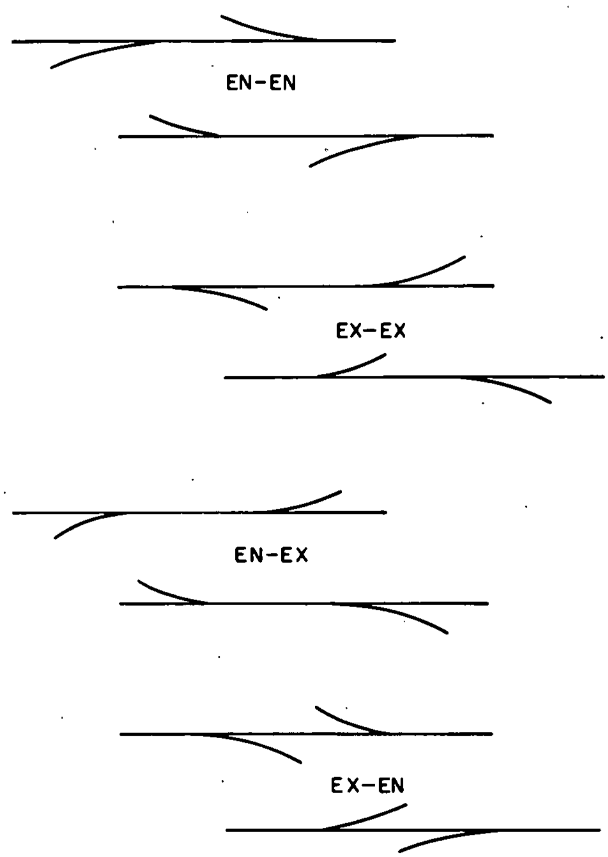


Figure C-10. Successive ramp arrangements with left-hand ramps.

APPENDIX D

CALIBRATION OF THE RECOMMENDED PROCEDURE

The equations that underlie the recommended procedure were developed from the macroscopic data, with the microscopic analyses serving as a guide and as a control in this effort. This appendix presents the results of the macroscopic analyses.

GUIDELINES

Early in the project, the following guidelines for the development of the procedure were developed with consideration for both data acquisition costs and probable return:

1. The procedure should be macroscopic in its approach, containing only that level of detail and sophistication necessary to properly specify the level of interest.
2. It should be as simple as practicable so that its principles are easily understood, but the drive for simplicity should not be at the sacrifice of significant accuracy.
3. It should be easily manipulated in both design and analysis and should present solutions so that ranges of acceptable values and alternates are clear.

MAJOR ISSUES

In the course of the research, several major questions were posed:

1. What are meaningful forms of the macroscopic relationship?
2. Should there be subcases according to configurational type?
3. Can equations be developed that cover the entire range of the data base (perhaps by subcase)? Must certain data be eliminated? Must level-of-service relationships be developed from the data?

4. What is the most meaningful period on which to aggregate macroscopic data? Should it be 6 min? * Hourly? These questions and their resolutions are addressed in the sections that follow.

FORM OF THE RELATIONSHIPS

The relationships that were to be developed for the macroscopic analyses not only had to take into account the microscopic observations and well-known macroscopic phenomena † but also had to mesh with the configurational emphasis early because both microscopic and macroscopic analyses within the research had shown the importance of this consideration. Moreover, the relationships had to consider explicitly a number of weaving-related variables (i.e., weaving volume V_w, section length L, and weaving width W) and the relationship to the nonweaving traffic occupying the roadway along with this weaving activity. Other weaving-related variables, such as the mix of the two weaving flows, were also candidates for inclusion.

Several mathematical forms were postulated, centering on the following ideas:

1. The basic dependent variable is the weaving volume V_w and the relationship should be so expressed.
2. The weaving width W itself should be thought of as the thing determined by the demand V_w in concert with the nonweaving traffic and other parameters.
3. The weaving service volume SW is a key concept although it is functionally dependent on several parameters.
4. The percentage of roadway occupied by the weaving traffic is functionally related to the percentage of the weaving traffic to the total traffic with this relationship modified by section length and other parameters.

Each of these is discussed in the following and specific forms developed consistent with these ideas and the microscopic results are analyzed via the macroscopic data base in the context of the major issues enumerated.

It should be noted that one of the major issues particularly affects the forms put forth: If there is no *a priori* or experimental specification of level-of-service categories, speed performance measures must be included in the forms developed for final evaluation.

Weaving Volume, V_w

The explicit dependence of V_w on other variables and certain parameters is both straightforward and appealing. It was observed that (1) there is a power relationship between V_w and section length L in which V_w is generally proportional to L^γ, $0 < \gamma < 1$; (2) as length L increases, weaving width W can decrease; (3) for fixed length L, weaving width W must increase as weaving volume V_w increases. These statements assume that neither weaving speed nor nonweaving volume and speed vary.

One may also note the effect of the mix of weaving volumes as reflected in the ratio of the smaller to the total weaving volumes (i.e., the parameter R): as R increases, the width W increases if all else is fixed.

These observations may be summarized in

$$V_w = \rho \, W^{\alpha+\beta R} \, L^\gamma \qquad \text{(D-1)}$$

where $\beta < 0$ and $0 < \gamma < 1$ should result from a calibration. Eq. D-1 was taken as the best form in early analyses in the research and was used in early attempts to develop a procedure.

Actually, in order to use linear regression as a tool,

$$\log V_w = A + B \log W + C\,(R \log W) + D \log L \qquad \text{(D-2)}$$

is more appropriate because of the nonlinearity of Eq. D-1. Moreover, the equal variance that must be associated with the dependent variable over the range of the independent variables is unlikely when considering V_w.

The form of Eq. D-2 is also amenable to addition of a term for speed relationships when one attempts to fit across the full range of the data. For instance, the fact that V_w must be smaller if S_w is larger and all else is unchanged leads to

$$\log V_w = (\text{Eq. D-2}) + E \log S_w \qquad \text{(D-3)}$$

where $E < 0$ should result from a calibration.

It is bothersome that Eq. D-3 is so independent of the nonweaving activity. The two activities—weaving and nonweaving—not only occur next to each other but actually overlap because the segregation of the two flow types is strong but not complete. Variations such as using ΔS or $\log \Delta S$ for the speed term in Eq. D-3 can address this.

Weaving Width, W

The foregoing assumes that, given all other conditions, one wishes to determine how much weaving volume V_w can be accommodated. One could generate plots of the form of HCM Figure 7.4, which can be "worked backwards" or the equation can be so manipulated as to enable one to determine the section length L that must exist to handle a specific volume V_w.

One may argue that in the real world the demand volumes appear and—for a given length L—the required width W is provided or the levels of service readjust so that a proper W is provided. The result of this action—and, thus, the true dependent variable—is the weaving width W. The relationship

$$W = A + B \log V_w + C \log L + D \log R \qquad \text{(D-4)}$$

realizes this. Variations on this form that produce a more meaningful and/or better fit to the data include (1) inclusion of speed-related terms involving S_w or ΔS; (2) replacement of some terms with their logarithms, antilogarithms, inverses, or powers; and (3) use of $\log W$ rather than W. Some of these represent nothing more than refinements of a specific fit within the range of the data available. As always, it would be hazardous and inappropriate to extend such refinements beyond the range of the data.

* One would usually consider 5 rather than 6 min, but the BPR data base was not amenable to this in terms of aggregating adjacent periods.
† For instance, the fact that increased length is beneficial.

Weaving Service Volume, SW

The weaving service volume is defined by

$$SW \triangleq V_w / W \tag{D-5}$$

and relationships such as Eqs. D-1 or D-2 can be used to develop expressions for the weaving service volume. For instance, if $\beta = 0$ and $\alpha = 1$ in Eq. D-1, $SW = \rho L^{\gamma}$. However, it is more likely that this is not true and that there is an inefficiency as W is increased such that SW decreases. Note that as W increases the compound weaving situations (more than one lane change needed to weave) become more significant. This SW does decrease due to inefficiency.

Although weaving service volume is an interesting derived measure, it shows no distinct advantage over the other approaches if it does not reduce the number of variables involved.

Percentage of Roadway

One may rationally argue that (1) the percentage of roadway W/N is proportional to the percentage VR that the weaving volume is of the total volume, all else being fixed; (2) as the section length L increases, this roadway percentage W/N decreases—rapidly at first—asymptotically to the same percentage as the volumes (i.e., VR); and (3) as the mix of weaving traffic (as measured by R) approaches equal competing flows, more roadway is required. This may be formalized as

$$\frac{W}{N} = (\alpha_0 + \alpha_1 VR)(1 + \alpha_2 R)(1 - \alpha_3 e^{-\alpha_4 L}) \tag{D-6}$$

or

$$\frac{W}{N} = (\alpha_0 + \alpha_1 VR)[1 - \alpha_2(1 - \alpha_3 R)e^{-\alpha_4 L}] \tag{D-7}$$

Eq. D-7 reflects the statements more accurately.

Figure D-1 shows the form of Eq. D-7. The equation has the flaw that the relationship between W/N and VR, all else fixed, is strictly linear. This may be overcome by forms involving powers and/or logarithms. The form

$$\frac{W}{N} = \alpha_0 VR^{(1+\alpha_1 R+\alpha_2 R^2)(1-\alpha_3 e^{-\alpha_4 L})} \tag{D-8}$$

accomplishes this, with the added refinement that with the R^2 added, it should describe the width effect better.

The logarithm of this last form (Eq. D-8) is more linear but requires both redefinition of variables and specification of α_4, as do Eqs. D-6 and D-7, in order to be suitable for linear regression analysis.

Similar to the observations made in discussing the weaving width form, speed terms and refinements may be considered.

USE OF DATA

The mathematical forms developed were reviewed for consistency with microscopic and macroscopic observations and analyses, for acceptable rationale, and for properties suitable for regression analyses. Although it was possible to rank them accordingly, some of the judgments were subjective. The final resolution must have been, therefore, in

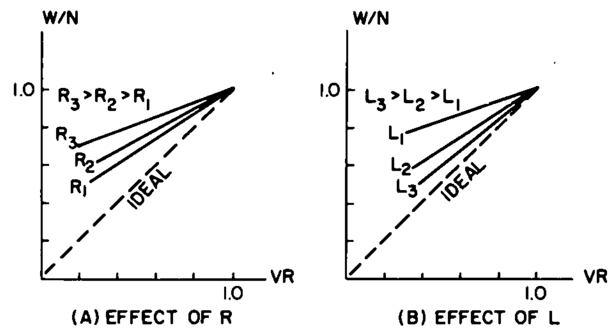


Figure D-1. Form of Equation D-7.

the quality of fit to the actual data; this resolution confirmed the evaluations. The data used were those comprising the composite date base described in Appendices I and II.*

Where strong relationships between variables were expected weak relationships resulted with some formulations. Second and third variables had to be considered simultaneously to relieve this. In other cases, some significant correlations existed between variables that one would have wished to be independent variables in a regression. These effects caused elimination of some forms because of the poor quality of the resultant fits. Some of the considerations of manipulating the data are presented.

Computation of W

The width, W, available to weaving vehicles was computed from

$$W = N - V_{nw}/SV \tag{D-9}$$

in which SV was determined from the adopted service volume relationships (refer to Chapter Two or Appendix E for the definition) for the observed nonweaving space mean speed S_{nw}.

Service Volume in a Weaving Section

The service volume definitions used in this report are adaptations of the HCM treatment and can be used in the same way as the HCM service volumes are.

In the course of the regression analyses, a side effort developed a relationship of the form

$$W = \alpha_0 - \alpha_1 \sqrt{V_{nw}} - \alpha_2 S_{nw} + \alpha_3 \log S_{nw} \tag{D-10}$$

that was highly correlated and involves only nonweaving variables. Of course, one would expect W to be highly dependent on V_{nw} and S_{nw}, as may be seen from Eq. D-9. Indeed, one may argue that the two can be equated and the service volume thus be revised.

Following this, or rather motivated by it, a regression analysis was done in which the total width N was considered as a variable dependent on two components, as $N_i = N_{nw,i} + W_i$ where $N_{nw,i} = f(V_{nw}, S_{nw,i})$ and $W_i =$

* Not included in this publication. See Appendix J herein for additional information.

g (previous variables) and the function minimized in the regression was

$$F = \sum_{i=1}^{\text{total}} (N_{\text{actual}} - N_i)^2 \qquad \text{(D-11)}$$

It was believed at one point that this would result simultaneously in a weaving width descriptor and a (nonweaving) service volume revision (via $N_{nw} = f(V_{nw}, S_{nw})$). The results, however, were not as good as other alternates in which the adopted SV's were used. Likewise, the relationship specified in Eq. D-10—although it added an apparent refinement—could be questioned as being simply a second analytic form that is different because it did not quite capture the full expression because of the limited terms available. The possible refinement did not aid in a more precise formulation and did not merit adoption.

Computation of SW

The weaving service volume SW is computed from $SW = V_w/W$, with W being computed as specified previously.

ANALYSIS TECHNIQUE

The prime tool in this macroscopic analysis was step-wise multiple linear regression executed by means of a standard computer package. The multiple correlation coefficient, indicating the reduction in the variation about the regression plane, was used as the index of the quality of the fit. Care was taken to add only terms that were statistically and physically meaningful. Appropriate standard statistical tests were performed.

SUBCASES AND RANGE

In the course of the analysis, it was determined that there should be two subcases classified by the configurations of major weave and ramp weave.

Attempts were made to (1) characterize the entire speed range within each of these subcases by common relations, (2) devise level-of-service relations as an outcome of the calibrations, and (3) characterize a lesser speed range by common relations.

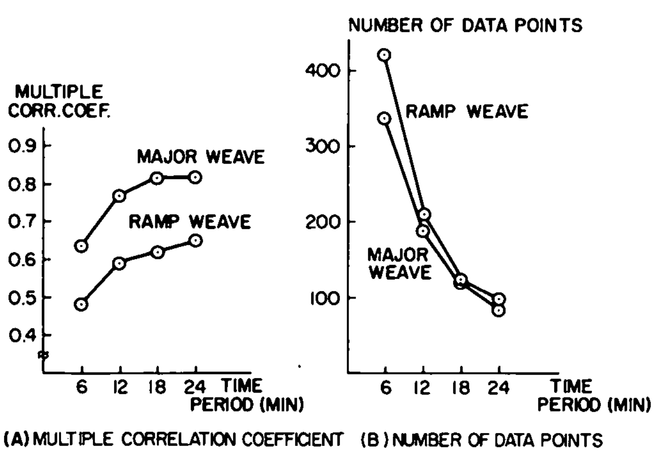


Figure D-2. Data required for the selection of a basic time period.

The determination of natural groupings of the data into levels of service was attempted by (1) grouping the data into small clusters of 75 points each ordered by S_w or L, (2) executing regression fits on consecutive cumulative aggregations of these groups (i.e., the first group, the first two groups, etc.), and (3) observing the behavior of the multiple correlation coefficient for this sequence. It was anticipated that the coefficient would increase as more data were added within an underlying natural grouping but would decrease as the natural grouping was exceeded and data were included from the next grouping. In this way, the consecutive natural groupings could be determined.

Unfortunately, this approach was contaminated by correlations with the small groupings among the candidate independent variables to some extent and did not conclusively establish distinct levels as was anticipated.

The attempts to fit relationships to all data were significantly poorer than those attempts to eliminate data for which $S_{nw} < 30$ mph. As a result (rather than as an assumption motivated by the HCM practices), the lower boundary of nonweaving level of service E can be identified as 30 mph. Likewise, the data for major weaves for which $S_{nw} \geqq 30$ cause $S_w \geqq 20$, so that the lower boundary for weaving level of service (major weaves) is 20 mph.

It is found that significant relationships can be developed by restricting the data only to the extent that $S_{nw} \geqq 30$ mph. This explains the result cited previously that consecutive groupings did not conclusively establish distinct levels of service.

EVALUATION, TIME PERIODS, AND CALIBRATION

The several mathematical forms and considerations outlined in the foregoing were evaluated by use of the macroscopic composite data base (BPR and project data bases combined, with some data reserved for data checks or because of peculiar features). The results may be summarized in two sets. The first set is:

1. Of the four basic forms—weaving volume, weaving width, weaving service volume, and roadway percentage—the best is the roadway percentage concept by a substantial margin. The next closest has a multiple correlation coefficient in the order of 0.2 lower. The specific relations are refinements on the logarithm form of Eq. D-8.

2. The issue of the appropriate time period is resolved by observing the multiple correlation coefficient as a function of the time period. At the same time, it must be recognized that the number of data points decreases as the basic time period is increased. Both aspects are illustrated in Figure D-2. The selection of a basic period of 18 min for the calibration is made from this information.

3. The relationships developed for the roadway percentage formulation have the following functional forms:

Major weaves: $$\log \frac{W}{N} = f(VR, S_w, L, R)$$

Ramp weaves: $$\log \frac{W}{N} = g(VR, \Delta S)$$

It may be observed that (1) the major weave relationship appears to be completely independent of nonweaving traffic performance,* and (2) the ramp-weave relationship does not involve section length L at all. It would appear that, so to speak, there is one degree of freedom not yet controlled.

The second set of results in this effort comes from an investigation intended to resolve this difficulty. For the major weaves, an attempt was made to find a relationship tying together the two speeds S_w and S_{nw}. For ramp weaves, an attempt was made to relate ΔS to L, there being no other reason to specify a ΔS in item 3 of the foregoing set.

The matrix of correlation coefficients for the 18-min data base was reviewed for major weaves and for ramp weaves. The relationships of interest did in fact exist therein. Indeed, for ramp weaves, the relationship (found by subsequent regression) specifying ΔS in terms of L and S_{nw} was stronger than the one found for log W/N.

Upon review, the importance of the ΔS relationship for ramp weaves is rational: the slippage between the two traffic streams (i.e., ΔS) is determined both by the "runway" length the weaving vehicles have and the speed of the main movement.

It is especially important that the relationships are divided, in effect, into a primary and a secondary equation for each configuration type. The primary equations are characterized by good multiple correlation coefficients across the entire $S_{nw} \geqq 30$ mph data range. The coefficients of the secondary relationships can be improved by a very relevant observation: although the secondary relationships are important so that a given situation is completely specified, a configurational limit also provides such specificity. Therefore, the data points with configurational limits may be removed from the calibration of the secondary relationships. The secondary relationships should be and are, in fact, thereby improved.

The final results of this effort are summarized in Table D-1. The ramp-weave primary equation includes the term $1/\sqrt{L+3}$ rather than the more apparent forms log L or $1/\sqrt{L}$ because, although the last had the best correlation of the common forms, review showed ΔS to be climbing too quickly to its asymptote with $1/\sqrt{L}$. The term incorporated had a slightly better correlation.

* Volume is certainly present via VR but there is no speed relationship included. It appears, from information developed to this point, that there may be a number of consistent S_{nw} and S_w.

Table D-2 summarizes the basic statistics of the four key equations. These include estimates of standard deviation of the dependent variable, the deviations associated with each coefficient, and the multiple correlation coefficients. The significance of each coefficient is tested under the hypothesis that it is indistinguishable from zero, and the significance of the over-all fit is also tested. The results are summarized in Table D-2. All coefficients are statistically different from zero and each over-all fit is acceptable.

Appendix E presents an integrated methodology using the results cited herein, the configuration results detailed in Appendix C, and level-of-service definitions made with the knowledge that they are neither forced because of a calibration nor imposed in a fashion so as to restrict a calibration. Consistent with the HCM and the probable level and interests of the user, the statistics of Table D-2 are not explicit in that procedure.

In the course of the final calibrations and analyses, the issue was raised as to whether the 18-min data established a regression plane that truly represented the underlying plane describing the situation most commonly of interest; namely, design/analysis for the peak within the hour. It was considered that a correction factor may have been required because of differences in 6- (really 5) and 18-min peaking. Regression planes were established using only peak 6-min data. It was found that they were statistically indistinguishable from the 18-min-based planes; therefore, no factor was necessary.

APPLICATION TO OTHER DATA; VALIDATION

Certain data were not used in the calibration data base used to establish the foregoing relationships. Although some of

TABLE D-1

RELATIONSHIPS OF MAJOR AND RAMP WEAVES

EQUATION TYPE	EQUATION DETAILS	EST. OF CORR. COEFF.
	(a) MAJOR WEAVE	
Primary	$\log\frac{W}{N} = -1.16 + 0.660\,VR - 3.10\,R(\log VR)e^{-0.1L} + 0.372 \log S_w$	$\rho = 0.812$
Secondary (holds only if W not constrained)	$\Delta S = 48.3 - 27.4 \log S_w - 0.146\,L$	$\rho = 0.637$
	(b) RAMP WEAVE	
Primary	$\Delta S = -109.5 + \frac{104.8}{\sqrt{L+3}} + 50.7 \log S_{nw}$	$\rho = 0.787$
Secondary (holds only if W not constrained)	$\log\frac{W}{N} = -0.615 + 0.606\sqrt{VR} - 0.00365\,(\Delta S)$	$\rho = 0.757$

TABLE D-2

SUMMARY OF STATISTICS FOR KEY EQUATIONS

EQUATION TYPE	EQUATION DETAILS	NO. OF POINTS	NO. DEPENDENT VARIABLES	STD ERROR OF ESTIMATE $S_{y/x}$	STD ERROR ON COEFF. S_{bi}	MULTIPLE CORR. COEFF.	SUM OF SQUARES REDUCED (%)	SIGNIF. OF COEFF. (T-TEST, $\alpha=0.05$) FROM DATA	FROM STD TABLE	SIGNIF. (NON-ZERO OR NOT)	FIT OF LINEAR FORM (F-STATISTIC, $\alpha=0.05$) FROM DATA	FROM STD TABLE	SIGNIF. (GOOD FIT OR NOT)	STATISTICS ON VARIABLES STD. DEV.	AVG.
Major weave:															
primary	$\log\frac{W}{N}=-1.16$	122	3	0.067	—	0.812	66.5	—	—	—	78.12	1.55	Good	−0.141	0.113
	$+0.660\ VR$	—	—	—	0.0438	—	—	15.04	1.98	S	—	—	—	0.525	0.174
	$-3.10\ R(\log VR)e^{-0.1L}$	—	—	—	0.317	—	—	−9.76	1.98	S	—	—	—	−0.0306	0.0223
	$+0.372\log S_w$	—	—	—	0.0718	—	—	5.18	1.98	S	—	—	—	1.55	0.0928
secondary	$\Delta S=+48.3$	81	2	3.94	—	0.637	41.4	—	—	—	27.51	1.63	Good	4.30	5.05
	$-27.4\log S_w$	—	—	—	5.22	—	—	−5.24	1.995	S	—	—	—	1.54	0.0854
	$-0.146\ L$	—	—	—	0.0346	—	—	−4.23	1.995	S	—	—	—	13.5	12.9
Ramp weave:															
primary	$\Delta S=-109.5$	121	2	4.62	—	0.787	62.2	—	—	—	97.28	1.55	Good	8.28	7.42
	$+104.8/\sqrt{L+3}$	—	—	—	10.0	—	—	10.44	1.98	S	—	—	—	0.321	0.0418
	$+50.7\log S_{nw}$	—	—	—	5.70	—	—	8.90	1.98	S	—	—	—	1.66	0.0737
secondary	$\log\frac{W}{N}=-0.615$	92	2	0.083	—	0.757	57.8	—	—	—	60.98	1.60	Good	−0.317	0.125
	$+0.606\sqrt{VR}$	—	—	—	0.0644	—	—	9.42	1.99	S	—	—	—	0.542	0.139
	$-0.00365\ (\Delta S)$	—	—	—	0.00119	—	—	−3.06	1.99	S	—	—	—	8.38	7.50

these data have flaws (such as experiment 3, as noted later), they were generally useful to check and to comment on the recommended procedure. The computer program described in Appendix F is used to execute the computations of the recommended procedure.

Gowanus Expressway

The Gowanus Expressway site is a 4,090-ft major weave on which data were collected by aerial photography early in the research. Details of this effort and the data are contained in Appendix XVI.* For the present purposes, the information summarized in Figure D-3 is sufficient.

Figure D-4 summarizes the results of the recommended procedure. Note that the weaving speed is quite accurately depicted, but that the nonweaving speed is actually poorer than one would expect via the recommended procedure (29 mph actual versus 36 mph estimated). This result is quite satisfactory, considering that the length involved (4,090 ft) is at the extreme of the calibration range. One may estimate that if $\Delta S \simeq -1.5$ mph were imposed, the procedure would have predicted $S_w \simeq 34.5$ mph, a 4-mph overestimate.

Project Experiment 6

Project experiment 6 was a 900-ft major weave, as shown in Figure D-5 (A). Table D-3 summarizes both the observed flows (6-min periods, shown as hourly rates) and the results of the analysis by the recommended procedure. Figure D-5 compares the actual and estimated speeds: the results are quite satisfactory.

It may be observed from Table D-3 that none of the section legs was inadequate nor was the section constrained by configuration.

* Not included in this publication. See Appendix J herein for additional information.

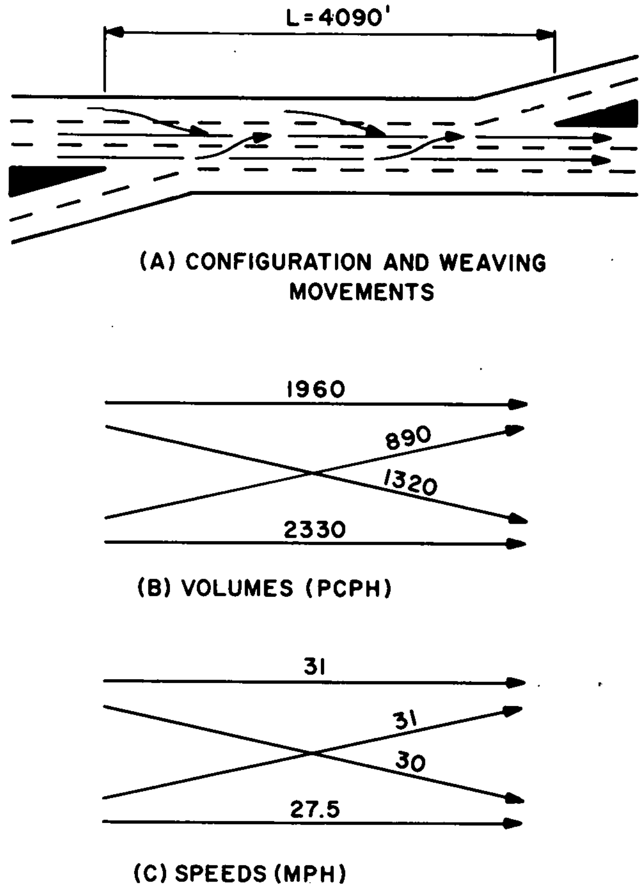


Figure D-3. Diagram of traffic movements, volumes, and speeds on the Gowanus Expressway.

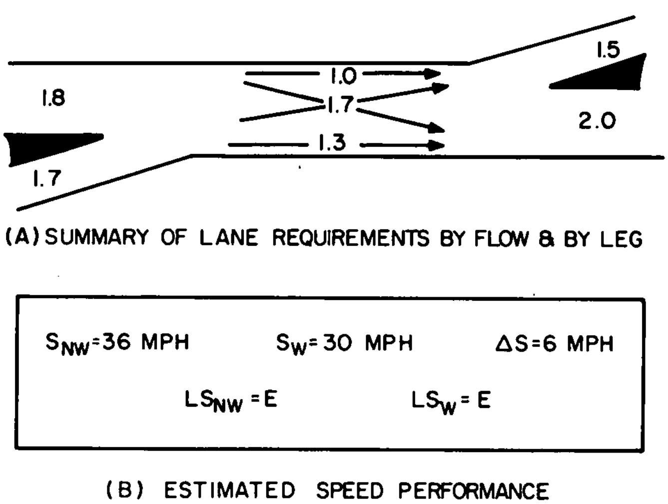


Figure D-4. Results of data analysis by recommended procedures of the Gowanus Expressway.

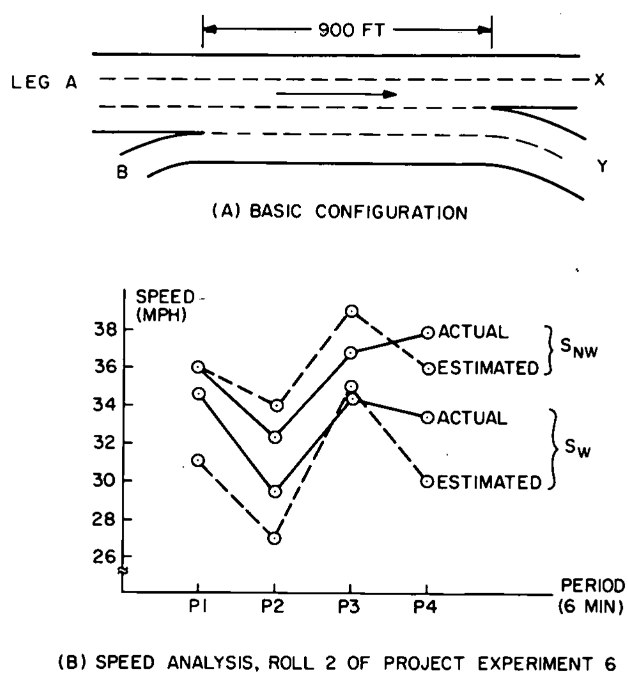


Figure D-5. Diagram of project experiment 6 and comparisons of the actual and estimated speeds.

Project Experiment 12

Project experiment 12 was a 750-ft ramp weave, as shown in Figure D-6 (A). Table D-4 summarizes both the observed flows (6-min periods, shown as hourly rates) and the results of the analysis by the recommended procedure. Figure D-6 (B) compares the actual and estimated speeds.

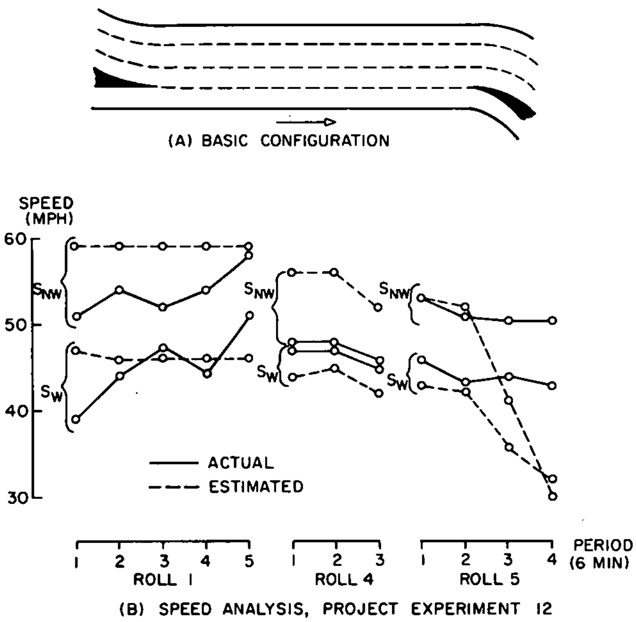


Figure D-6. Diagram of project experiment 12 and comparisons of the actual and estimated speeds.

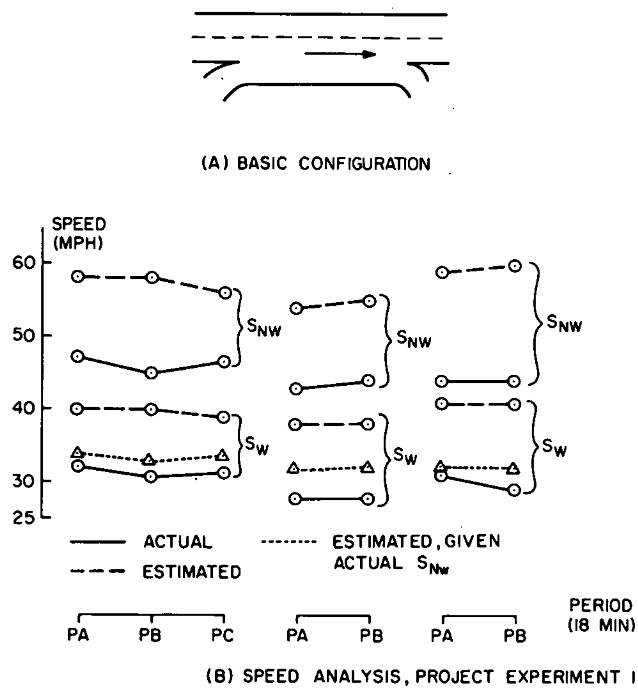


Figure D-7. Diagram of project experiment 1 and comparisons of the actual and estimated speeds.

Although the results were within reason, it must be observed that (1) the predictions of S_{nw} near 60 mph were not achieved and (2) the predicted rapid decay of speed in roll 5 was not realized. In the first case, the posted speed limit of 55 mph might have had an effect. In the second case, the fact that the rapid decay did not occur can be likened to the "supersaturation" effect in a liquid during the transition, but more data would be required to determine if and when the actual decay did occur. Unfortunately, the data shown are at the end of the available record.

One may also observe from Table D-4 that only leg B occasionally has a service limitation (requiring 1.1 lanes, with only 1.0 available) and that there is no configurational constraint. This is not too significant a disruption because it implies only that the entering ramp traffic functions at a slightly poorer level.

Because movement 4 is so substantial a part of V_{nw} (see Table D-4) and is so influenced by the weaving movements, one may wish to consider the speed of movement 1 only when investigating the actual data. Movement 1 is generally 2 mph or so higher than the actual S_{nw} shown in Figure D-6 (B).

Project Experiment 1

The preceding evaluations (project experiments 6 and 12) were done with 6-min field data. Some evaluations were also done with 18-min data. The problems that arise in these evaluations are not attributable to the use of 18-min rather than 6-min data.

Project experiment 1 was a 460-ft ramp weave, as shown in Figure D-7 (A). Table D-5 summarizes both the observed flows (18-min periods, shown as hourly rates) and the results of the analysis by the recommended procedure. Figure D-7 (B) compares actual and estimated speeds.

The results of this analysis were, at first inspection, rather poor. The actual S_{nw} and S_w were both substantially lower than expected. However, this site had a posted speed limit of 45 mph. Note that the S_{nw} was limited to this range * and that the possible S_{nw} was not achieved. When the actual S_{nw} was used, a significant improvement in the estimated S_w was achieved, as is also indicated in Figure D-7.

If the speed limit is assumed, so that a field-measured S_{nw} need not be obtained, an S_w of 33 mph is estimated. This is also significantly better than originally estimated, and highlights the fact that the speed limit may control although speeds well above it could exist.

Project Experiment 3

Project experiment 3 was a 420-ft ramp weave, as shown in Figure D-8 (A). Table D-6 summarizes both the observed flows (18-min periods, shown as hourly rates) and the results of the analysis by the recommended procedure. Figure D-8 (B) compares the actual and estimated speeds.

The results of this analysis were quite dissatisfying but, in retrospect, have a rational explanation. This site was in the midst of a work area and had a posted advisory limit of

* Actually, the mainline vehicles are going 1 to 2 mph faster than indicated by the S_{nw} because movement 4 is included in the computation of S_{nw}.

TABLE D-3

ROLL 2 OF PROJECT EXPERIMENT 6

PROBLEM TITLE	N	L	LVL OF SER NWE	LVL OF SER WEA	SPEEDS NWE	SPEEDS WEA	CONFIG CONSTR	W	DEL S	VOLUMES(PCPH) 1	VOLUMES(PCPH) 2	VOLUMES(PCPH) 3	VOLUMES(PCPH) 4	LANE REQUIREMENTS A-X	LANE REQUIREMENTS WEA	LANE REQUIREMENTS B-Y	LGA	LGB	LGX	LGY
EXP6R2P1	4.	9.0	[illegible]	E	36.	31.	NO	2.7	6.	1280.	1350.	630.	1100.	0.7	2.7	0.6	1.4	0.9	1.0	1.3
EXP6R2P2	4.	9.0	E	E	34.	27.	NO	2.5	7.	1780.	1590.	640.	1060.	0.9	2.5	0.6	1.8	0.9	1.3	1.4
EXP6R2P3	4.	9.0	D2	D2	39.	35.	NO	2.7	4.	1270.	1370.	520.	990.	0.7	2.7	0.6	1.5	0.8	1.0	1.3
EXP6R2P4	4.	9.0	E	E	36.	30.	NO	2.5	6.	1780.	1300.	500.	1060.	1.0	2.5	0.6	1.7	0.8	1.2	1.3

TABLE D-4

PROJECT EXPERIMENT 12

PROBLEM TITLE	N	L	LVL OF SER NWE	LVL OF SER WEA	SPEEDS NWE	SPEEDS WEA	CONFIG CONSTR	W	DEL S	VOLUMES(PCPH) 1	VOLUMES(PCPH) 2	VOLUMES(PCPH) 3	VOLUMES(PCPH) 4	LANE REQUIREMENTS A-X	LANE REQUIREMENTS WEA	LANE REQUIREMENTS B-Y	LGA	LGB	LGX	LGY
EX12R1P1	4.	7.5	B	D	59.	47.	NO	1.9	13.	1506.	123.	642.	284.	1.8	1.9	0.3	1.9	1.1	2.6	0.5
EX12R1P2	4.	7.5	B	D	59.	46.	NO	1.7	13.	1670.	140.	440.	310.	1.9	1.7	0.4	2.1	0.9	2.5	0.5
EX12R1P3	4.	7.5	B	D	59.	46.	NO	1.8	13.	1530.	170.	500.	390.	1.8	1.8	0.5	2.0	1.0	2.4	0.6
EX12R1P4	4.	7.5	B	D	59.	46.	NO	1.6	13.	1750.	80.	400.	280.	2.1	1.6	0.3	2.2	0.8	2.5	0.4
EX12R1P5	4.	7.5	B	D	59.	46.	NO	1.6	13.	1840.	130.	340.	340.	2.1	1.6	0.4	2.2	0.8	2.4	0.5
EX12R4P1	4.	7.5	B	D	56.	44.	NO	1.8	12.	1960.	91.	747.	485.	1.8	1.8	0.4	1.9	1.1	2.5	0.5
EX12R4P2	4.	7.5	B	D	56.	45.	NO	1.9	12.	1818.	232.	717.	444.	1.7	1.9	0.4	1.9	1.1	2.4	0.6
EX12R4P3	4.	7.5	C	D	52.	42.	NO	1.7	10.	2731.	269.	634.	516.	1.9	1.7	0.4	2.1	0.8	2.4	0.6
EX12R5P1	4.	7.5	C	D	53.	43.	NO	1.8	11.	2443.	247.	691.	454.	1.9	1.8	0.3	2.1	0.9	2.4	0.5
EX12R5P2	4.	7.5	C	D	52.	42.	NO	1.8	10.	2600.	190.	870.	530.	1.8	1.8	0.4	2.0	1.0	2.4	0.5
EX12R5P3	4.	7.5	D	E	41.	36.	NO	1.9	5.	2828.	333.	980.	808.	1.6	1.9	0.5	1.8	1.0	2.2	0.7
EX12R5P4	4.	7.5	E	E	30.	32.	NO	2.0	-2.	3350.	310.	1070.	630.	1.7	2.0	0.3	1.8	0.9	2.2	0.5

30 mph. Preliminary checks at the site indicated that the traffic was flowing at reasonable volume and speeds, and the adverse or limiting effects of the improvements under way or signing along that road were judged to be negligible. The results tended to contradict this judgment, particularly because the other ramp-weave analysis exhibited no such problems.

TABLE D-5

PROJECT EXPERIMENT 1

PROBLEM TITLE	N	L	LVL OF SER NWE	LVL OF SER WEA	SPEEDS NWE	SPEEDS WEA	CONFIG CONSTR	W	DEL S	VOLUMES(PCPH) 1	2	3	4	LANE REQUIREMENTS A-X	WEA	B-Y	LGA	LGB	LGX	LGY
EXPIPER1*	3.	4.6	B	D	58.	40.	NO	1.6	18.	1063.	313.	636.	40.	1.3	1.6	0.1	1.7	0.8	2.1	0.4
2*	3.	4.6	B	D	58.	40.	NO	1.6	18.	1120.	246.	643.	90.	1.3	1.6	0.1	1.6	0.9	2.1	0.4
3*	3.	4.6	B	D	56.	39.	NO	1.5	17.	1310.	237.	630.	100.	1.4	1.5	0.1	1.7	0.8	2.1	0.4
4*	3.	4.6	C	E	54.	38.	NO	1.5	16.	1530.	267.	810.	70.	1.4	1.5	0.1	1.6	0.8	2.1	0.3
5*	3.	4.6	B	D	55.	38.	NO	1.5	17.	1380.	223.	766.	66.	1.4	1.5	0.1	1.6	0.8	2.2	0.3
6*	3.	4.6	B	D	59.	41.	NO	1.6	19.	980.	153.	687.	56.	1.3	1.6	0.1	1.5	1.0	2.3	0.3
7*	3.	4.6	A	D	60.	41.	NO	1.7	19.	833.	193.	693.	47.	1.1	1.7	0.1	1.4	1.1	2.1	0.3

*These correspond in order to the periods cited in Figure D-7 (B)

Summary

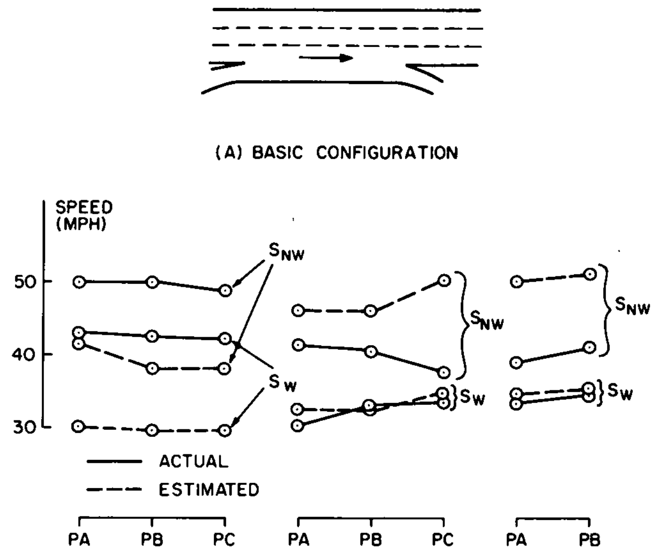
The foregoing cases illustrate the utility of the recommended procedure. None of these cases was included in the calibration data base.

The validation results can be summarized as follows:

CASE	NUMBER OF POINTS	DURATION/POINT (MIN)	RESULTS
1. Gowanus Expressway (major weave)	1	3	Quite satisfactory
2. Project experiment 6 (major weave)	4	6	Quite satisfactory
3. Project experiment 12 (ramp weave)	12	6	Adequate. Caution: Consider posted speed limits and overloaded legs.
4. Project experiment 1 (ramp weave)	7	18	Good, but must note posted speed limit.
5. Project experiment 3 (ramp weave)	8	18	Poor, but posted speed limit of 30 mph and improvements under way. In retrospect, an error to collect.

It should be noted that the validation cases emphasize lessons in the application of the procedure: posted speed limits may control, and individual leg overloads may cause disruptions.

Project experiment 17, a 2,600-ft major weave, was not included in the validation because its data can be grouped into three classes: (1) heavy volume with backup into the section from downstream construction, (2) light volume with one of the weaving volumes not present, and (3) light volume with speeds of weaving and nonweaving flows comparable (as they should be at the higher speeds, according to the recommended procedure). Data in the last category are very limited, again reflecting the variability of conditions at a site. This was recognized as a particular hazard at this site, and field data were taken on several days. Detailed analysis of the data from this apparently good collection effort revealed the limitations.



(B) SPEED ANALYSIS, PROJECT EXPERIMENT 3

Figure D-8. Diagram of project experiment 3 and comparisons of the actual and estimated speeds.

TABLE D-6

PROJECT EXPERIMENT 3

PROBLEM TITLE	N	L	LVL OF SER NWE	LVL OF SER WEA	SPEEDS NWE	SPEEDS WEA	CONFIG CONSTR	N	DEL S	VOLUMES(PCPH) 1	2	3	4	LANE REQUIREMENTS A-X	WEA	B-Y	LGA	LGB	LGX	LGY
EXP3PER1	4.	4.2	E	F	37.	28.	NO	1.5	9.	4503.	246.	475.	29.	2.5	1.5	0.0	2.6	0.3	2.7	0.2
2 SPECIAL FACTOR(LATERAL CLEARANCE ETC) OF 0.92 IS USED...THIS IS NOT SAME AS HCM TABLE 9.2 IN THAT LANE WIDTH IS CORRECTED FOR INDEPENDENTLY																				
2	4.	4.2	E	F	33.	26.	NO	1.6	7.	4554.	337.	540.	40.	2.4	1.6	0.0	2.6	0.3	2.7	0.2
3 SPECIAL FACTOR(LATERAL CLEARANCE ETC) OF 0.92 IS USED...THIS IS NOT SAME AS HCM TABLE 9.2 IN THAT LANE WIDTH IS CORRECTED FOR INDEPENDENTLY																				
3	4.	4.2	E	F	35.	27.	NO	1.7	8.	4318.	424.	579.	43.	2.3	1.7	0.0	2.5	0.3	2.6	0.3
4 SPECIAL FACTOR(LATERAL CLEARANCE ETC) OF 0.92 IS USED...THIS IS NOT SAME AS HCM TABLE 9.2 IN THAT LANE WIDTH IS CORRECTED FOR INDEPENDENTLY																				
4	4.	4.2	D	E	46.	32.	NO	1.6	14.	3905.	424.	554.	65.	2.4	1.6	0.0	2.6	0.4	2.7	0.3
5 SPECIAL FACTOR(LATERAL CLEARANCE ETC) OF 0.92 IS USED...THIS IS NOT SAME AS HCM TABLE 9.2 IN THAT LANE WIDTH IS CORRECTED FOR INDEPENDENTLY																				
5	4.	4.2	D	F	48.	33.	NO	1.7	15.	3696.	598.	536.	90.	2.3	1.7	0.1	2.6	0.4	2.6	0.4
6 SPECIAL FACTOR(LATERAL CLEARANCE ETC) OF 0.92 IS USED...THIS IS NOT SAME AS HCM TABLE 9.2 IN THAT LANE WIDTH IS CORRECTED FOR INDEPENDENTLY																				
6	4.	4.2	C	E	50.	34.	NO	1.5	16.	3750.	464.	413.	123.	2.4	1.5	0.1	2.7	0.3	2.6	0.4
7 SPECIAL FACTOR(LATERAL CLEARANCE ETC) OF 0.92 IS USED...THIS IS NOT SAME AS HCM TABLE 9.2 IN THAT LANE WIDTH IS CORRECTED FOR INDEPENDENTLY																				
7	4.	4.2	C	E	50.	34.	NO	1.6	16.	3707.	514.	446.	54.	2.4	1.6	0.0	2.7	0.3	2.7	0.4
8 SPECIAL FACTOR(LATERAL CLEARANCE ETC) OF 0.92 IS USED...THIS IS NOT SAME AS HCM TABLE 9.2 IN THAT LANE WIDTH IS CORRECTED FOR INDEPENDENTLY																				
8	4.	4.2	C	E	51.	34.	NO	1.5	16.	3742.	517.	348.	65.	2.4	1.5	0.0	2.7	0.3	2.6	0.4
9 SPECIAL FACTOR(LATERAL CLEARANCE ETC) OF 0.92 IS USED...THIS IS NOT SAME AS HCM TABLE 9.2 IN THAT LANE WIDTH IS CORRECTED FOR INDEPENDENTLY																				
9	4.	4.2	E	F	38.	28.	NO	1.7	10.	3783.	837.	293.	362.	2.1	1.7	0.2	2.6	0.4	2.3	0.7
10 SPECIAL FACTOR(LATERAL CLEARANCE ETC) OF 0.92 IS USED...THIS IS NOT SAME AS HCM TABLE 9.2 IN THAT LANE WIDTH IS CORRECTED FOR INDEPENDENTLY																				
10	4.	4.2	D	F	49.	34.	NO	1.7	16.	3680.	724.	384.	87.	2.3	1.7	0.1	2.7	0.3	2.5	0.5

*These correspond in order to the periods cited in Figure D-8(B)

APPENDIX E

THE RECOMMENDED WEAVING PROCEDURE

The procedure presented herein is the product of work conducted under National Cooperative Highway Research Program (NCHRP) Project 3-15.

The procedure is suitable for use in both design and analysis. In addition to relating the various parameters of the weaving section to the traffic characteristics and performance, it incorporates explicit consideration of the section configuration. In design, this means consideration of whether the required weaving space can actually be delivered with the proposed lane arrangement. In analysis, this means consideration of the limit imposed on weaving space availability by the lane arrangement.

This appendix presents the actual computational steps and procedures to be followed in design and analysis. Examples are included. A computer program is also available to use as an alternate means of solution; it is described in Appendix F.

The following are some of the general concepts or ideas integral to the procedure:

- Space mean speeds rather than operating speeds are used to define levels of operation.
- The service volume concepts of the HCM are adapted and used for the nonweaving traffic.
- Volumes are considered in passenger car equivalents (pce), in units of passenger cars per hour (pcph). Adjustments of vehicles per hour (vph) to pcph is made in accordance with the HCM.
- Levels of service are defined separately for weaving and nonweaving flows.
- Although balanced design (comparable levels of service) is sought, it is recognized that configuration may prevent it from being realized.
- As far as basic relationships are concerned, there are two sets of equations—one for major weave sections and one for ramp-weave sections.*

DEFINITIONS AND TERMINOLOGY OF VARIABLES

Weaving area terminology requiring definition includes:

- balanced—a section is said to be balanced when the same level of service is delivered to both nonweaving and weaving traffic.
- BPR—Bureau of Public Roads.
- configuration constrained—a situation in which a lane arrangement limits the weaving width W that can be delivered.
- FHWA—Federal Highway Administration (formerly BPR).
- HCM—the *Highway Capacity Manual* (1965 edition unless otherwise specified).

* A major weave has three or more legs each having two or more lanes. A ramp weave is a standard auxiliary lane arangement with one lane on and one lane off. The basic types are illustrated in Figure E-1.

- leg—an input or output roadway.
- major weave—a weaving section in which three or more legs each have two or more lanes; see Figure E-1 (B), (C), and (D).
- pcphpl—abbreviation for passenger car per hour per lane, the unit in which service volumes are expressed.
- PHF—peak-hour factor, the hourly volume divided by the hourly rate during the peak 5 min of that hour; this is as defined in the *Highway Capacity Manual.*
- ramp weave—a highway mainline with an on-ramp, off-ramp sequence (both single lanes) connected by an auxiliary lane; see Figure E-1 (A).
- SMS—space mean speed (mph).
- through lane—a lane on which at least one of two weaving flows (see Fig. E-1 (C) or (D), legs A-Y or B-X) can achieve its "weave" without a lane change; a lane may be a through lane for either or both weaving flows; when it is so for only one flow, it should be aligned with the greater flow in order that the benefit of a through lane can be realized.

All terminology and practices not specifically otherwise defined in this procedure are consistent with the HCM.

Note that when a PHF is used, the design (both levels of service and speeds) is being done for the busiest 5 min of the peak hour, and not for the entire hour.

Nomenclature requiring definition includes the variables:

V_w = total weaving volume, in passenger cars per hour (pcph)
V_{wc} = total weaving volume (HCM notation), in pcph
V_{w2} = smaller weaving volume, in pcph
V_{nw} = total nonweaving volume, in pcph
V_{TOT} = total volume, in pcph
V = total volume (HCM notation), in pcph
SV = service volume, in pcph or pcph per lane (pcphpl)
S_w = speed of weaving volumes, in mph
S_{nw} = speed of nonweaving volumes, in mph
$\Delta S = (S_{nw} - S_w)$ = difference in speeds, in mph
L = section length, in hundreds of feet *
N = section width, in total lanes
W = width for weaving, in lanes *
N_{nw} = width for nonweaving, in lanes *
$VR = V_w/V_{TOT}$ = ratio of weaving to total volumes
R = ratio of smaller weaving to total weaving volume

Additional volume parameters are shown in Figure E-2. Some volumes—particularly V_{w2} and V as used in the HCM—will generally be measured in vehicles per hour (vph); likewise, SV may be specified in pcph or in per lane values and may be corrected for standard adjustments when volumes are in vph. The proper course will be apparent in any given case by the context.

* These may be fractional numbers.

CONFIGURATION

The explicit consideration and awareness of configuration (section lane arrangement, including numbers of lanes on each leg) is an important and essential element of the recommended weaving procedure. All else that is done should be done in this context.

It is of prime importance in design that the configuration be such that:

1. The computed W can in fact be delivered.
2. The lanes required for each outer flow (nonweaving flow) can in fact be delivered.
3. The lanes on each input/output leg can in fact handle the volumes at the level of service desired.

One of the prime results of the research leading to the recommended procedure was the determination of the maximum width that can actually be used by weaving traffic. It was found that this depended upon configuration type. The summary of results is given in Table E-1. The various configurations cited are shown in Figure E-1.

Since it is generally accepted that a "choice lane" should be provided for a major weave type of configuration, most designs will automatically incorporate a through lane (Figure E-1 (C) or (D), which have "choice" lanes at the bifurcation proper, as opposed to Figure E-1 (B), which does not). It does not follow, however, that this will necessarily always correspond to the direction of the greater weaving flow. The benefit of $W = 3.6$ is realized completely, however, only when it does correspond.

In analysis, knowledge of the configuration (lane arrangement) and Table E-1 dictates the maximum W. It also provides information on the adequacy of the section for its nonweaving (outer) flows.

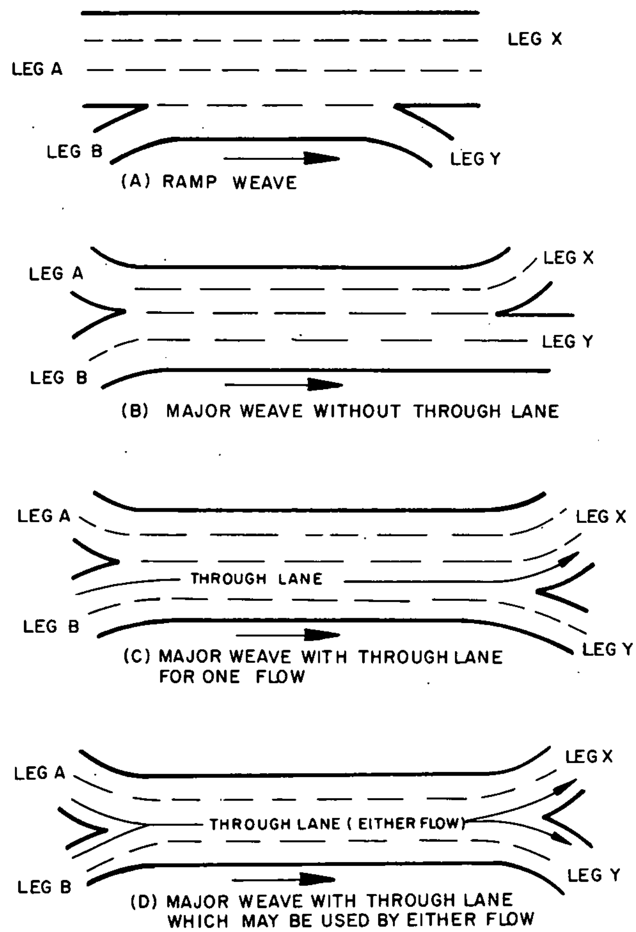


Figure E-1. Diagrams of various configurations of weaving areas.

LEVELS OF SERVICE; SERVICE VOLUMES

Separate levels of service for weaving and nonweaving flows were defined in accordance with the observations of the data base.

The levels of service as defined in HCM Table 9.1 were adapted for use with the nonweaving volumes. The adaptations were that (1) space mean speeds rather than operating speeds were used throughout, including the calibrations; (2) the service volume values were interpolated between those commonly specified as necessary, the interpolation being linear with respect to travel times; and (3) the boundary between levels D and E was taken as 38 mph.

Operating speed is defined in the HCM as "the highest over-all speed at which a driver can travel on a given highway under favorable weather conditions and under prevailing traffic conditions without at any time exceeding the safe speed as determined by the design speed on a section-by-section basis." It is the fastest reasonable speed. Space mean speed, on the other hand, is "the average of the speeds of vehicles within a given space or section of roadway at a given instant," or "the average speed of a specified

TABLE E-1

MAXIMUM WEAVING WIDTH W VARIES WITH CONFIGURATION

CONFIGURATION	WIDTH (LANES)
Ramp weave	2.3
Major weave with a crown line	2.6 to 2.7 [a]
Major weave with through lane on direction of greater weaving flow	3.6

[a] An estimate. The data base was deficient in these cases.

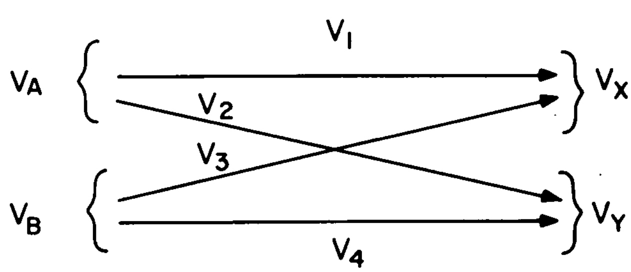


Figure E-2. Diagram of volume parameters for a weaving area.

group of vehicles based on their average travel time over a section of roadway."

Space mean speed has the advantage of having an operational definition—it can be measured unambiguously. Moreover, most data are collected in ways that yield space mean speeds, not operating speeds. This includes most speed-volume data that underlie curves of the service volume-speed relationship. In regard to weaving analysis, the 1963 BPR data base could meaningfully yield only space mean speeds.

Because of both the exigencies of the data base(s) available and the more basic judgment that operating speed is unnecessarily ambiguous as to measurement, space mean speed was adopted as the speed measure. The question was raised of how the service volume-speed relationship of the HCM could have been calibrated with operating speeds. For low volumes in the data at hand, the space mean speeds approached the speeds expected in the HCM.

In the recommended procedure, space mean speeds were the ones used. The calibration and use are consistent within the recommended procedure, and the procedure is self-contained in this respect. Comparisons with the HCM are done on the basis of (service) volumes in the examples, not speeds alone.

Should the user wish to obtain operating speed estimates, however, he can use the equation developed by Makigami, et al. (*6*):

$$OS = AS + \frac{DS}{10}\left[1 - \frac{V}{C}\right] \qquad \text{(E-1)}$$

in which

OS = operating speed (mph);
AS = average running speed or space mean speed (mph);
DS = design speed or speed limit (mph); and
V/C = volume-to-capacity ratio.

With a 55-mph speed limit and $V/C = 0.40$, the increment is 3.3 mph. This is at level of service A for a six-lane facility (three lanes per direction). At level of service B, the increment would only be 2.3 mph.

Returning to the definitions adopted for the weaving procedure:

1. The nonweaving level of service for both major weaves and ramp weaves will be defined analogous to the HCM, as discussed above.
2. The weaving level of service for ramp weaves will be defined identical to the nonweaving level of service.
3. The weaving level of service for major weaves will be defined so that, at "balanced" or equilibrium operation, both nonweaving and weaving traffic will have the same level-of-service designation.

The last definition is achieved by observing the balance that occurs between weaving and nonweaving flows when W is not constrained by configuration. The speed differential that then exists is shown in Figure E-2; this is based on the calibration data base.

Although the speed difference ΔS implied in Figure E-3 is dependent on length as well as S_w, it is not highly sensitive to length. The curve for $L = 12.5$ is therefore used rather than adding an unnecessary complexity.

The level-of-service definitions are contained in Table E-2. Note that level of service D is subdivided for major weaves, so that either $\Delta S = 5$ mph or $\Delta S = 2$ mph can be specified in design.

Note that one level of service characterizes both nonweaving flows. For a given design, the practitioner may observe that one is not accurately portrayed. For instance, a small ramp-to-ramp flow on a ramp weave is controlled by the weaving level of service. Other than this case (which

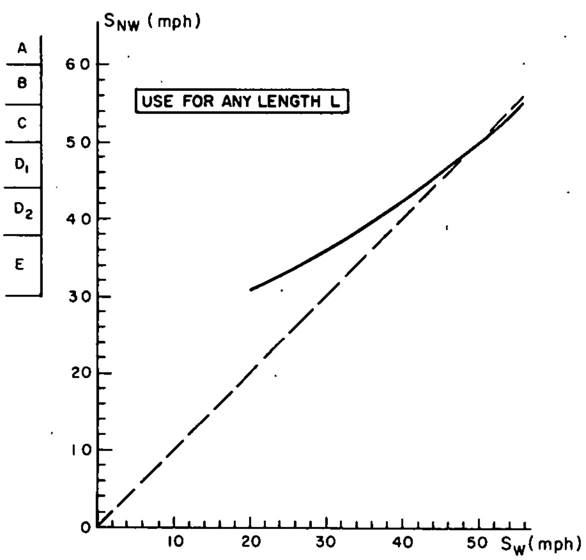


Figure E-3. Speed relationships for major weave, design case. Note: Insensitivity to L exhibited in ΔS formula (Table E-3) generating this relationship. Curve shown for $L = 12.5$. This does not imply insensitivity to L in a major weave. See Table E-3.

TABLE E-2

LEVEL-OF-SERVICE DEFINITIONS

	NONWEAVING (ALL) AND RAMP-WEAVE WEAVING		MAJOR WEAVE (WEAVING TRAFFIC ONLY)	
LEVEL OF SERVICE	RANGE (MPH)	DESIGN SPEED (MPH)	RANGE (MPH)	DESIGN SPEED (MPH)
A	60 and up	60	60 and up	—[a]
B	55 to 60	55	55 to 60	55
C	50 to 55	50	50 to 55	50
D	38 to 50	—[b]	33 to 50	—[b]
E	30 to 38	30	20 to 33	20
F	30 and under	—	20 and under	—

[a] Improbable; no such case observed in the calibration data base; use procedure with this awareness.
[b] For ramp-weave: 38 mph
For major weave:
D_2: $\Delta S=5$: $S_{nw}=38$ and $S_w=33$
D_1: $\Delta S=2$: $S_{nw}=44$ and $S_w=42$

will not significantly affect the computations), this refinement is not generally recommended, as what is desired is a descriptor of the over-all section in relatively simple terms, consistent with accuracy.*

The service volumes associated with the nonweaving levels of service are summarized in Figure E-4. As noted, they are based on HCM values, with linear interpolation (with respect to travel times) used to find values between those specified.

The service volume characterizing a section is to be based on the entrance leg with the greater number of input lanes. This is the approach used in handling the calibration data. In addition to determining N_{nw}, the service volume is to be used in checking the input/output lanes required, or the adequacy of those provided.

Note that service volume is given in passenger cars per hour per lane. All computations assume that the volumes have been adjusted for grade, trucks, lane width, and lateral clearance. The peak-hour factor (PHF) is built into the service volume curves. It is as defined in the HCM.

* Moreover, one would frequently become enmeshed in considerations of "how much" of the *W* is on "which side" of the section that requires a sophistication inappropriate to the purpose of the procedure. Insights can be gained, however, by the more sophisticated user.

THE BASIC RELATIONSHIPS

This section presents the equations describing weaving section operation. It also presents some discussion of these relationships and the physical variables involved.

The best relationships describing weaving traffic were developed starting from the assumption that *W/N* is proportional (actually, functionally related) to *VR*. That is, that the percentage of width required by weaving vehicles is directly related to the percentage of the total traffic that they constitute.

Note that this one relationship—*W/N* dependent principally upon VR—involves both types of flow (weaving and nonweaving) in the determination of *W*. This is reasonable because although the flows are significantly segregated as they enter the section there is a physical overlap and, thus, interaction in the space they occupy.

A summary of the basic relationships for major weaves and ramp weaves is given in Table E-3. For each configuration type (major weave or ramp weave), there are two governing equations:

1. A "primary" relationship that holds under all conditions and that was calibrated with all available data. Note

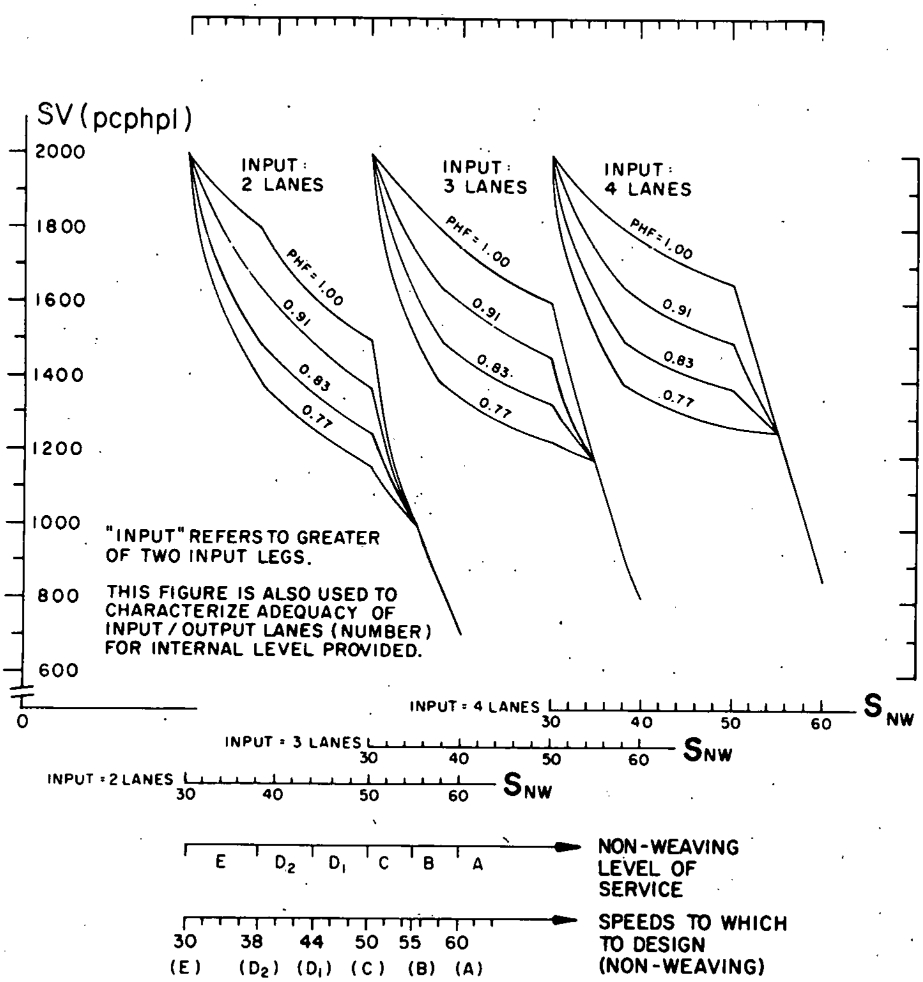


Figure E-4. Service volumes accommodated for various specified values of S_{nw}.

TABLE E-3

RELATIONSHIPS OF MAJOR AND RAMP WEAVES

EQUATION TYPE	EQUATION DETAILS	EST. OF CORR. COEFF.
	(a) MAJOR WEAVE	
Primary	$\log\frac{W}{N} = -1.16 + 0.660\, VR - 3.10\, R(\log VR)e^{-0.1L} + 0.372 \log S_{w}$	$\rho = 0.812$
Secondary (holds only if W not constrained)	$\Delta S = 48.3 - 27.4 \log S_{w} - 0.146\, L$	$\rho = 0.637$
	(b) RAMP WEAVE	
Primary	$\Delta S = -109.5 + \frac{104.8}{\sqrt{L+3}} + 50.7 \log S_{nw}$	$\rho = 0.787$
Secondary (holds only if W not constrained)	$\log\frac{W}{N} = -0.615 + 0.606\sqrt{VR} - 0.00365\,(\Delta S)$	$\rho = 0.757$

that the sample correlation coefficient exceeds 0.8 in both cases.

2. A "secondary" relationship that holds only when W is not configuration constrained and that was calibrated with only those data that did not border on configuration constrained.

The ramp-weave secondary relationship in particular would be significantly weaker if an attempt were made to fit it with all available data.

The importance of the "secondary" relationships is in removing an indeterminacy that superficially seemed to exist. Without them, analysis of a section could not yield a specific, most probable description of operations unless W was at its maximum. They are "secondary" only in that they do not always hold.

The fact that the relationship defining ΔS is of greater importance for ramp weaves than for major weaves is logical. In a ramp-weave situation, even one in which W is constrained, ΔS is dependent on the "runway" provided to the weaving vehicles (this is determined by L), and—for a given L—the weaving flow is "carried along" to a certain extent by the motion, speed, and opportunities of the mainline. Whenever possible, W will readjust to suit the situation at hand, as is reflected in the "secondary" equation for ramp weaves.

It is interesting that length L is a significant determinant of section operation, but L's significance dissipates quickly as it is increased. In both major weaves and ramp weaves, by far the greatest part of the advantage of length is achieved by 2,000 ft.

It should be noted that no ramp weaves above 2,000 ft were used in the calibrations, nor are they often built. The utility of such added length is not related directly to weaving section performance; that is, perhaps a ramp weave that need be only 1,500 ft long is merited, but external considerations dictate the ramp location such that a 2,500-ft length is created.

In the case of the major weave, benefit still accrues above 2,000 ft in increasing length although most of the benefit would have already been realized. Although the calibration data base contains lengths up to 4,600 ft, only 10 percent of the base is above 2,000 ft. One should expect less precision in the results for rather long sections.

It is possible to show that as the major weave section is made very long the level of operation does not generally reach the level defined by $SV = V_{TOT}/N$ (effective nonweaving). While this may be due to the limitations of the calibration, it must be remembered that (1) the merge and diverge turbulence will always exist, regardless of length, and (2) intensive lane changing exists at the beginning of the section due to just the intensive presegregation, adding to the turbulence.

In regard to which set of equations should be used for which design problems, it must be recognized that the flows and the VR value will generally give insight into which configuration type should be used in particular design problems. In general, if VR is less than 0.4, use the ramp-weave set; otherwise, use the major weave set. In analysis, inspection of the configuration will aid in determining the proper equation to use.

Figure E-5 illustrates the range of VR values for the two configuration types that were exhibited in the data base from which the calibration was made.

DESIGN

The basic design problem is the design of a section to a specified level of service for given volumes. Some variations on this (testing different lengths, for instance) are, in fact, analysis problems. Others (maximum V_w for specified conditions, for instance) are modifications of the basic approach. Both can be treated as analysis problems.

The first step is always adjustment of the measure of volume to passenger cars per hour.

The configuration type (major weave or ramp weave) may generally be selected by inspection of the flows and the probable or desired input/output lanes per leg. The design computations may then be done for the appropriate configuration type.

Major Weave

Given a level of service to which to design, one may solve the problem in one of two ways: analytically or graphically. Steps of the analytic solution (with some graphic steps) are presented first, with an explanation of the procedure.

1. From the definitions of level of service (Table E-2), determine the speeds involved.
2. From Figure E-4, knowing PHF if appropriate and assuming a value for the greater number of input lanes based on input flows, find a service volume (SV) for the S_{nw}. Divide this into V_{nw} to obtain N_{nw}, the lanes for nonweaving flow.
3. For a given N of interest, compute W. If W is not unreasonable (Table E-1), go to step 5.
4. If the computed W is unreasonable, set W to the maximum (Table E-1). Then $N_{nw} = N - W$. Compute $SV = V_{nw}/N_{nw}$. Using Figure E-4, determine S_{nw} and thus the nonweaving level of service.
5. With whichever W is appropriate, compute W/N. Recall that S_w was determined in step 1. From the "primary" equation of Table E-3, determine L. If it happens that $e^{-0.1L}$ equals a negative value in this determination, there is no feasible L.
6. If there is no feasible L, modify the N assumed (step 3) or the level of service desired, or simply report the fact. Even if L is feasible, one may wish to compute the L for several values of N.

The graphic technique is based on Figures E-6, E-7, and E-8, which incorporate all of the above steps. Given a desired level of service and judging the greater number of input lanes, execute the following construction:

1. Enter Figure E-6 with S_{nw}, determining SV by reflecting from the proper "inputs" curve. Continue the line through SV to the proper V_{nw}, reflecting down to the N_{nw} value.
2. Draw a line from the N_{nw} thus found through the N of interest, thus determining W. If the W is not unreasonable (Table E-1, or $W = 3.6$), go to step 4.
3. If the W thus found is unreasonable, fix W at the appropriate maximum. Work backward through N to find N_{nw}. With N_{nw}, reflect off V_{nw} to determine SV and then off the appropriate "inputs" curve to determine S_{nw} and thus nonweaving level of service.
4. With whichever W is appropriate, find W/N. Proceed to nomograph in Figure E-7.
5. Draw line 1 from W/N to VR on Nomograph 1 (Fig. E-7). Extend this line to T_1. A point on T_1 is thus defined. Draw line 2 from this point to S_w. Ignore the S_{nw} values—they are there for analysis.
6. Extension of line 2 defines a value h. Enter Nomograph 2 in Figure E-8 with this value. Draw line 3 from R to VR. This defines a point on T_2. Draw line 4 from this point to h. Extend this line to L. This defines the specific length L required.

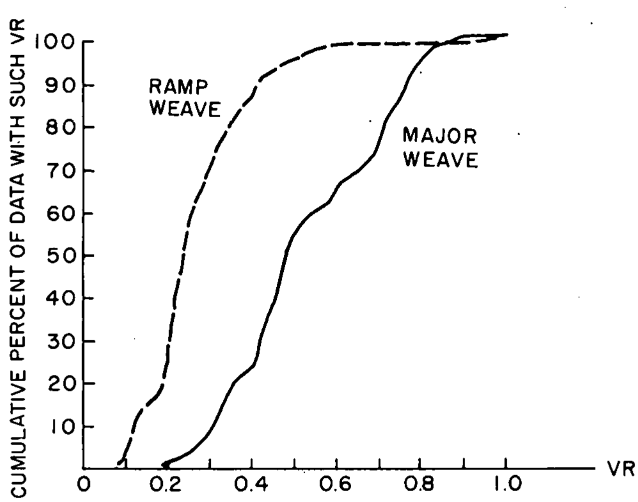


Figure E-5. Comparison of the range of VR *values for the ramp-weave and major weave configurations.*

Given the value of L from either approach, one may then proceed (knowing SV for the nonweaving level of service) to compute the number of lanes desired on each leg. Knowing this and the W required (perhaps the maximum), one may design the final configuration.

Ramp Weave

It will be necessary to specify only one level of service in the ramp-weave design; it should be the through (nonweaving) level of service. Again, there are two approaches to the solution—analytical and graphical.

It will be observed that it is not generally possible to attain a "balanced design" (comparable levels of service for weaving and nonweaving). This can only be achieved by specifying balance as the objective, rather than a specific level of service. This is discussed within the basic design approach.

The analytic approach (with some graphical steps) is presented first, with an explanation of the procedure. The all-graphic technique is then presented.

1. From the definitions of level of service (Table E-2), determine the S_{nw} desired.
2. From Figure E-4, knowing the PHF if appropriate and noting a probable mainline number of lanes from the given information, find a service volume SV for the S_{nw}. Divide this into V_{nw} to obtain N_{nw}, the lanes for nonweaving flow.
3. For the N of interest, compute W. If W does not exceed 2.3 (see Table E-1), go to step 6.

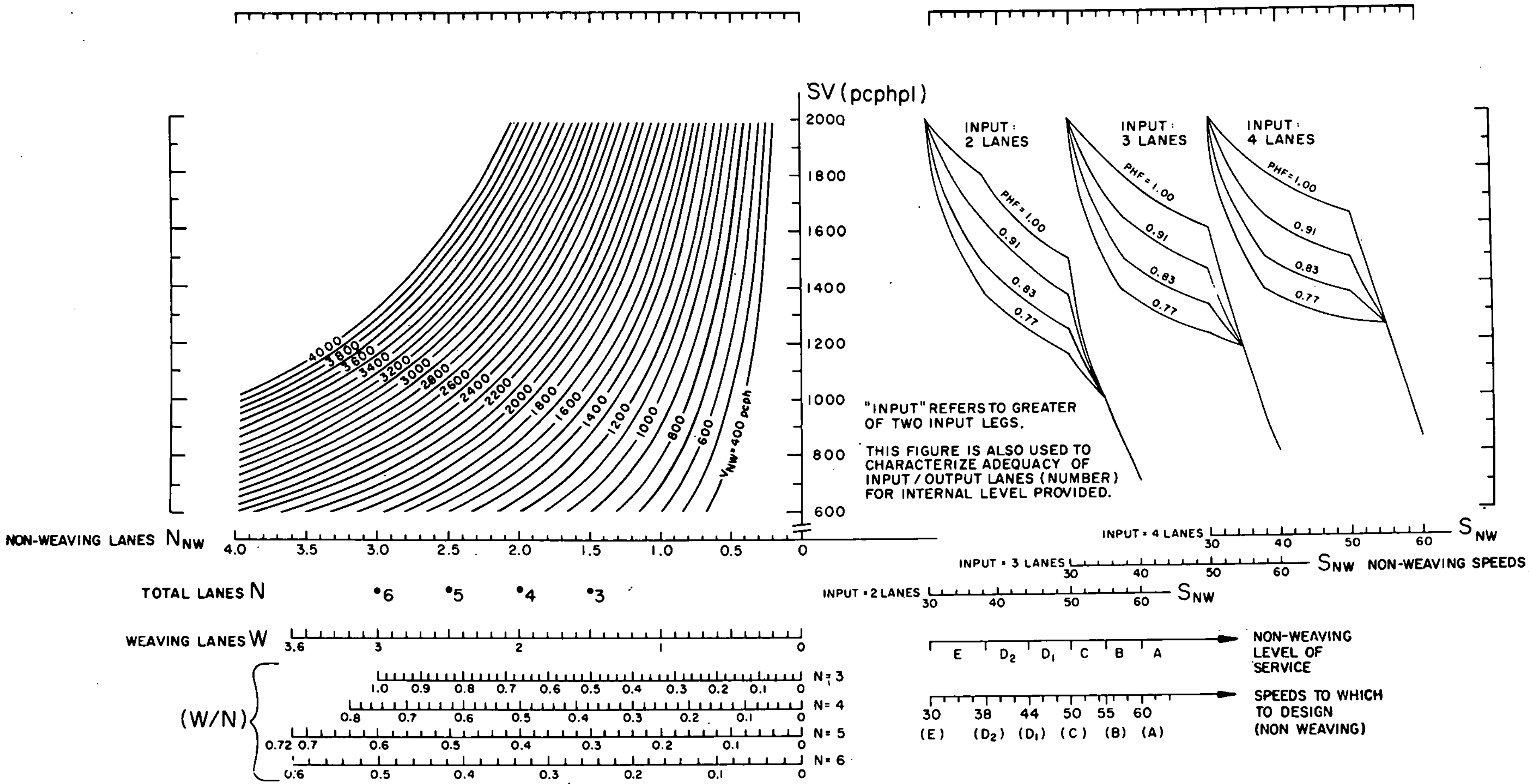


Figure E-6. This figure shows the relationships among S_{nw}, SV, N_{nw}, and W for ramp weaves. It is a part, along with the nomographs in Figures E-7 and E-8, of the graphic technique for computing configuration parameters for a major weave section to a specified level of service for given volumes.

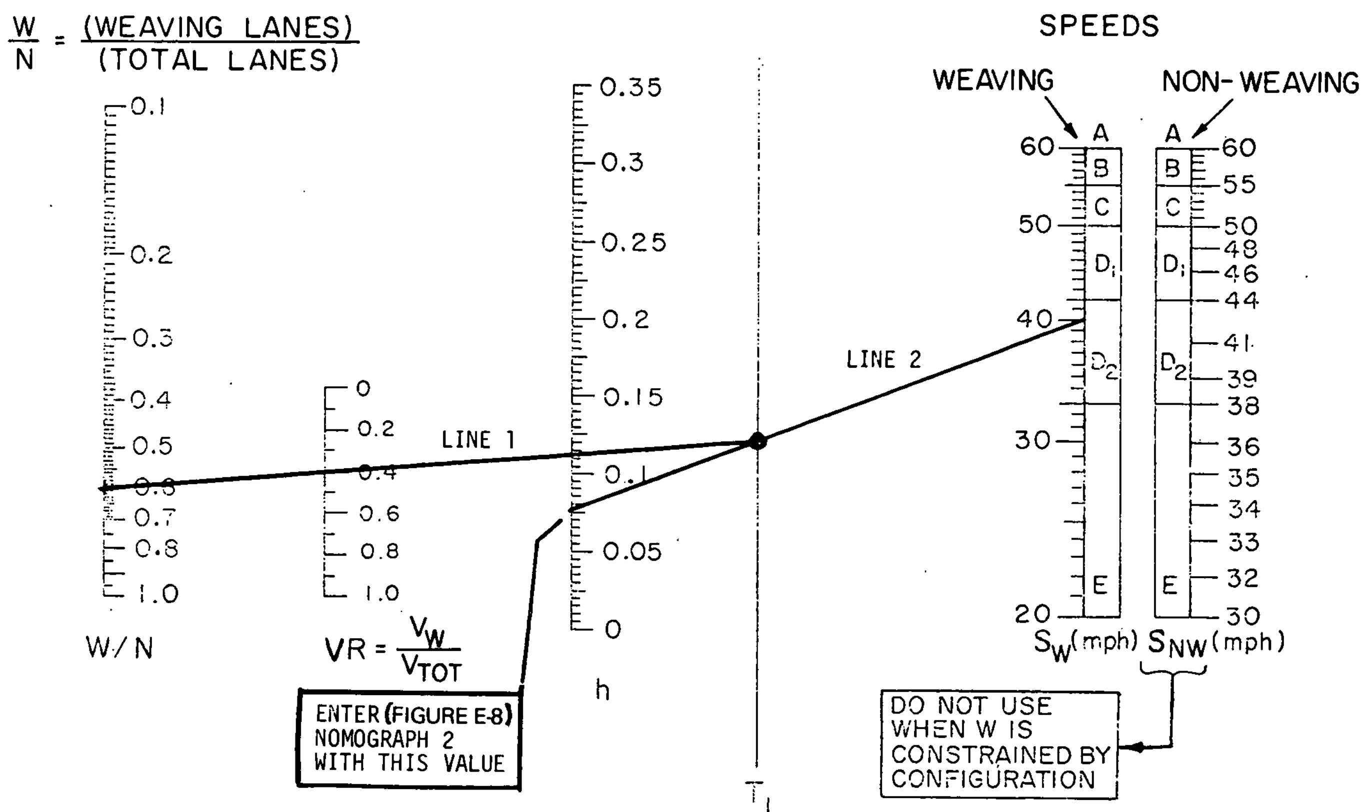


Figure E-7. Nomograph 1 for major weave design/analysis.

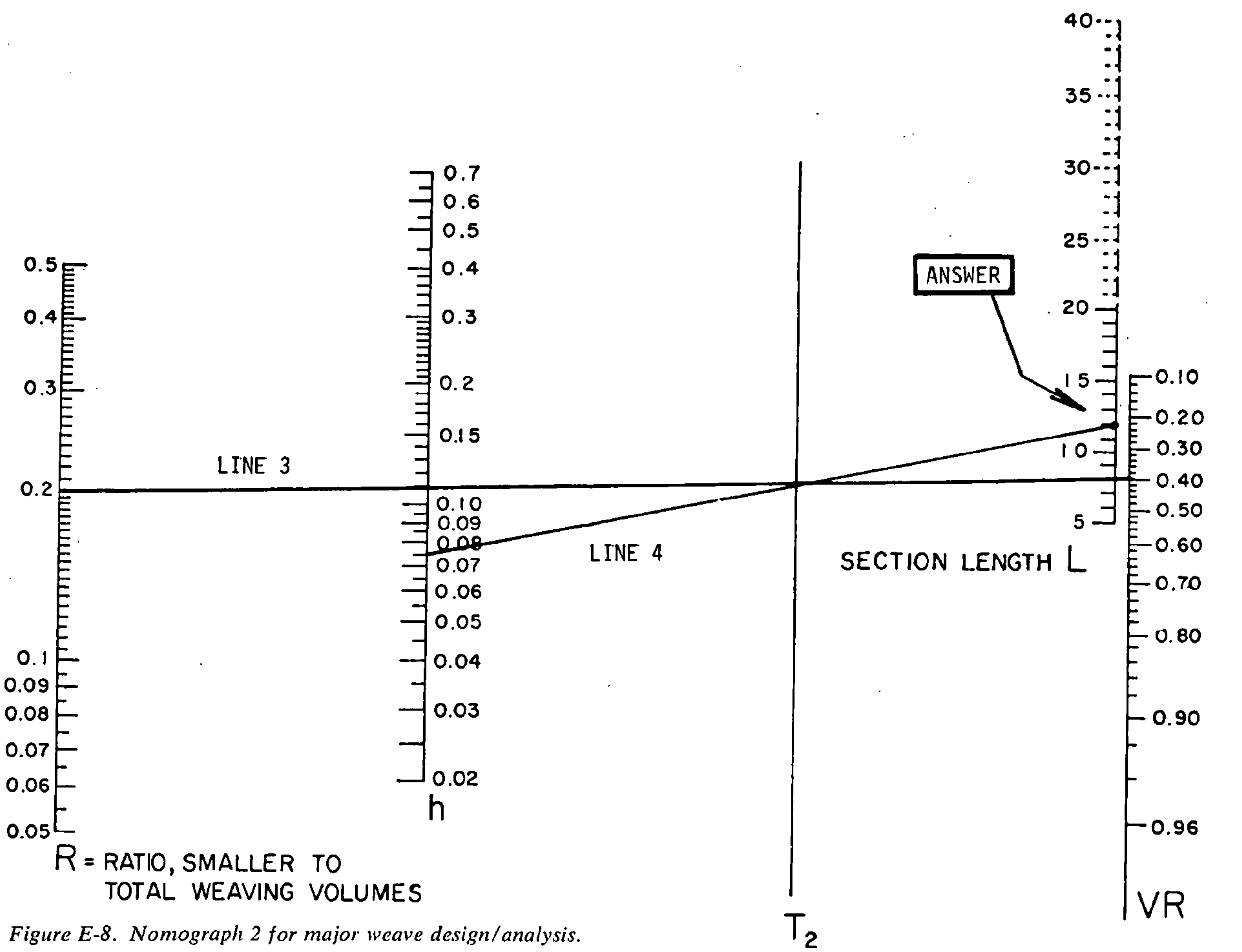


Figure E-8. Nomograph 2 for major weave design/analysis.

4. If the computed W does exceed 2.3, set W to this maximum. Compute $N_{nw} = N - W$. Compute $SV = V_{nw}/N_{nw}$. Using Figure E-4, determine S_{nw} and thus the nonweaving level of service.

5. Continuing with the maximum W being used, the length L may now be chosen. It will determine ΔS, as evidenced in the primary ramp-weave equation of Table E-3. It is recommended that L be chosen so that $\Delta S = 0$, which constitutes a "balanced" design. If the length required for $\Delta S = 0$ cannot be provided, the same equation will determine ΔS for the length that can be provided. For information, this equation is plotted as Figure E-9. If W exceeds 2.3, the design problem is completed.

6. If the computed W does not exceed 2.3, the secondary ramp-weave equation of Table E-3 will determine ΔS. The primary ramp-weave equation will then determine the requisite length L. If more length than is minimally necessary is in fact provided, S_w will increase at the expense of S_{nw}. There will be a readjustment of W. Study of this situation is described in the "analysis" section.

The designer must be cautioned that one may "protect" the nonweaving traffic at the expense of the weaving traffic. It is an easy trap to fall into when (1) a high level of service is specified for nonweaving traffic, (2) this high level implies a large ΔS, or (3) the ΔS is realized by a short length. The design is met but the operation is undesirable—the two levels of service are disparate, and even the nonweaving vehicles near the ramps are severely affected; the high S_{nw} is probably due to median lane traffic being effectively isolated.

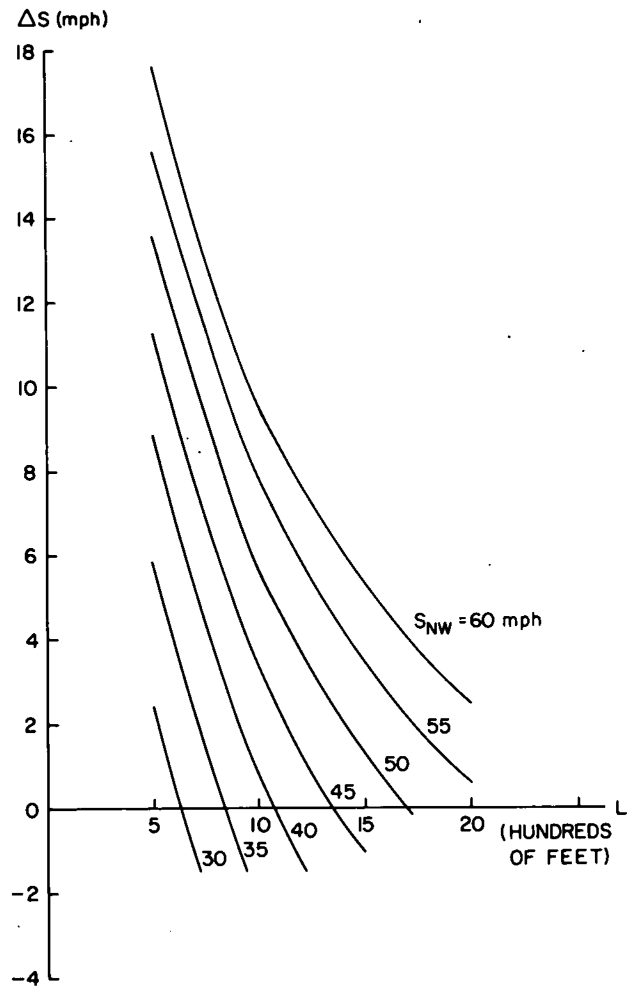


Figure E-9. Plot of the "primary" equation for ramp weaves.

The designer should, therefore, exercise caution. If he sees a large ΔS, he should redesign with a lower nonweaving level of service.

The graphic technique is based on Figure E-10* and Nomograph 3 shown in Figure E-11, which incorporate all of the above steps. Given a desired nonweaving level of service and judging the number of mainline lanes, execute the following constructions:

1. Enter with S_{nw}, determining SV by reflecting from the proper "inputs" curve. Continue the line through SV to the proper V_{nw}, reflecting down to the N_{nw} value.
2. Draw a line from the N_{nw} thus found through the N of interest, thus determining W. If W is less than 2.3, go to step 5.
3. If W exceeds 2.3, work backward from $W = 2.3$ through N to find N_{nw}. With N_{nw}, reflect off V_{nw} to determine SV and then off S_{nw} and thus determine the nonweaving level of service.
4. Taking advantage of this W constraint, draw line 2 on the nomograph (Fig. E-11) from $\Delta S = 0$ to the S_{nw} value determined. The length L is thus determined. If this L cannot be provided, pivot line 2 through the permissible L for the S_{nw} specified. This determines ΔS and thus weaving level of service. For W-constrained cases, this completes the design.
5. For W less than 2.3, draw line 1 on Nomograph 3 (Fig. E-11) from W/N to VR. Extend this line to determine ΔS. Draw line 2 from ΔS to S_{nw}, thus determining L. From ΔS, one determines S_w and, thus, the weaving level of service (Table E-2). If ΔS is large, the designer should consider designing to a lower nonweaving level of service.

Given the SV from either approach, one may then proceed to compute (verify) the number of lanes required on each leg.

The designer should be cautioned that in some ramp-weave designs, it may be advantageous to attempt an alternate major weave design. This may occur because of ramp volumes (on or off), because of permissible length L causing an undesirable ΔS, or because of a significant ramp-to-ramp flow being controlled by the weaving flows.

The designer should also be reminded that there are situations in which weaving sections are not the appropriate solution. Given constraints on L and N, and/or very substantial volumes, it may happen that no permissible section will operate acceptably. Some alternate solution—rearrangement of ramps, elimination of the section by other redesign, etc.—would then have to be sought.

* The only difference between Figures E-6 and E-10 is the maximum W indicated on the axis.

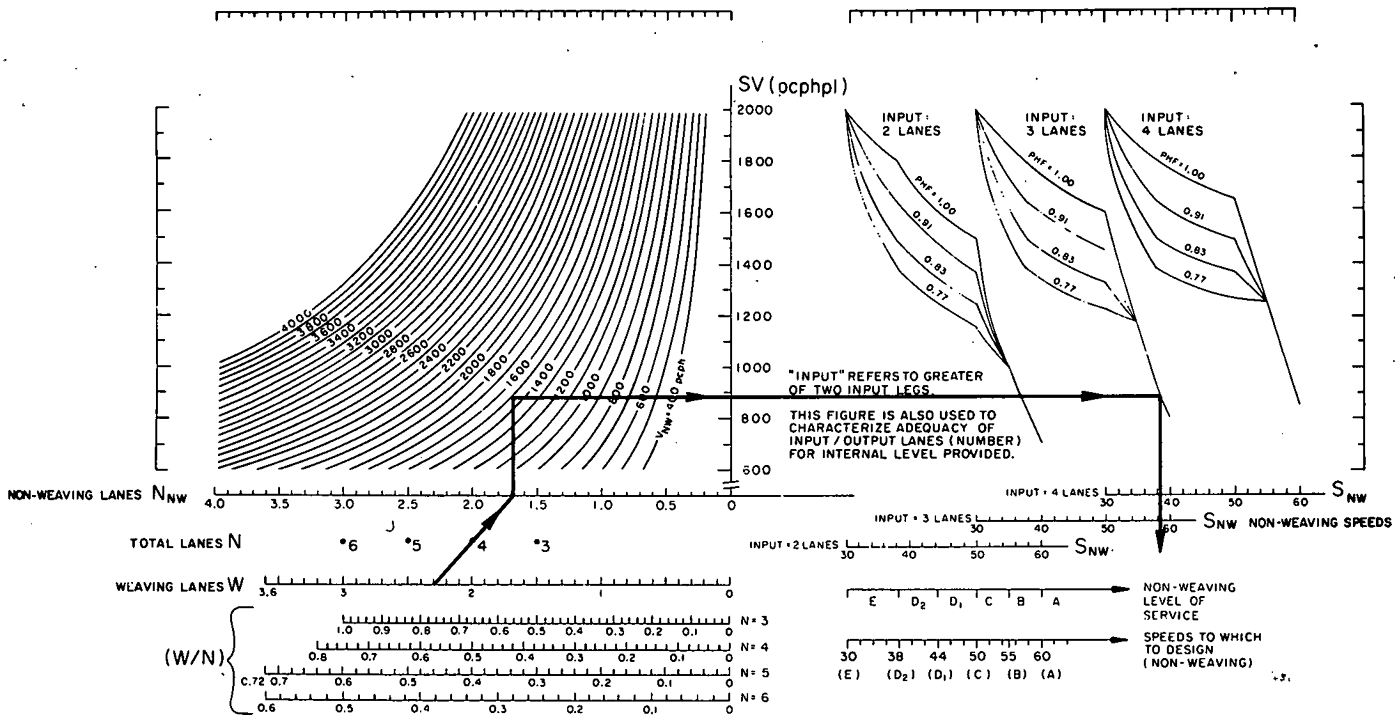


Figure E-10. This figure shows the relationships among S_{nw}, SV, N_{nw}, and W for ramp weaves. It and Nomograph 3 in Figure E-11 comprise the graphic technique for computing configuration parameters for a ramp-weave section.

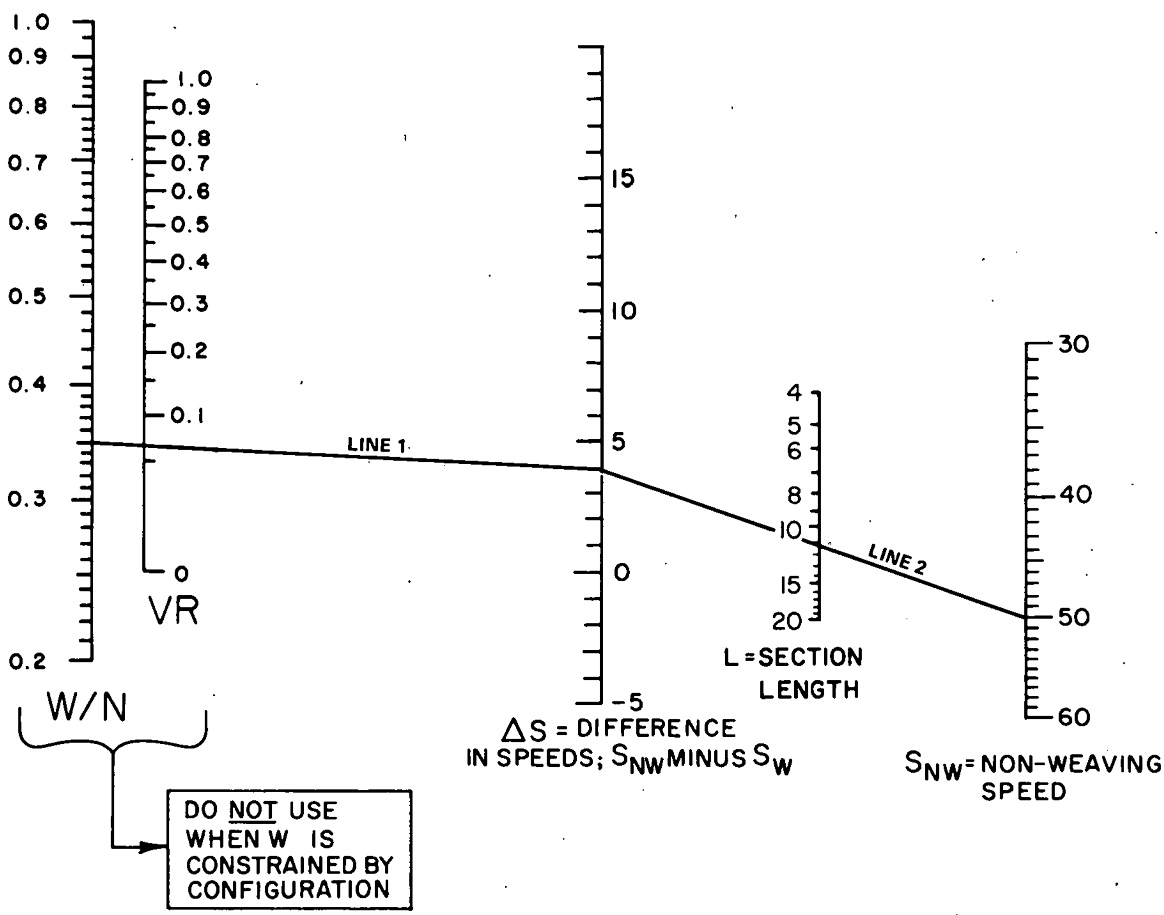


Figure E-11. Nomograph 3 for ramp-weave design/analysis.

DESIGN EXAMPLES

Example 1

Two highways are to intersect as shown in Figure E-12, with the flows indicated. The volumes are shown in passenger cars per hour. It is desired to have this section operate at level of service B. Due to other considerations, the lanes (input/output) should be as illustrated, if at all possible.

Immediately one may note that (1) the input/output arrangement dictates $N = 4$ and (2) the appropriate approach is certainly one of major weave.

The problem first will be solved according to the "analytic" procedure specified previously:

1. From Table E-2 for level of service B, $S_{nw} = S_w =$ 55 mph.
2. For "Input: 2 lanes" on Figure E-4, $SV = 1{,}000$ pcphpl. Thus $N_{nw} = (800 + 1{,}400)/1{,}000 = 2.20$.
3. $W = (4 - 2.20) = 1.80$. This is a reasonable value. Go to step 5.
4. Does not apply in this case.
5. $W/N = 0.45$. From primary major weave equation of Table E-3,

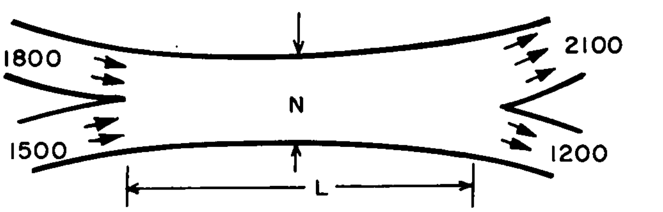
$$\begin{aligned}\log(0.45) &= -1.16 + 0.660\,(0.333)\\ &\quad -3.10\,(0.364)(\log 0.33)\, e^{-0.1L}\\ &\quad + 0.372 \log(55)\end{aligned}$$

so that $-0.347 = -1.16 + 0.220 + 0.538e^{-0.1L} + 0.647$ or $e^{-0.1L} = -0.100$, which cannot be.

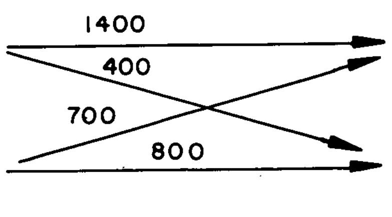
It must be recalled (if one is solving this analytically) that e^{-x} is always positive.

One concludes that a design to level of service B is not possible. Consider a design to level of service C. Lacking information, assume a peak-hour factor (PHF) of 0.91. The same procedural steps are again taken.

1. From Table E-2, $S_{nw} = S_w = 50$ mph.



(A) SECTION OF INTEREST, VOLUMES IN PCPH



(B) VOLUMES BY MOVEMENT

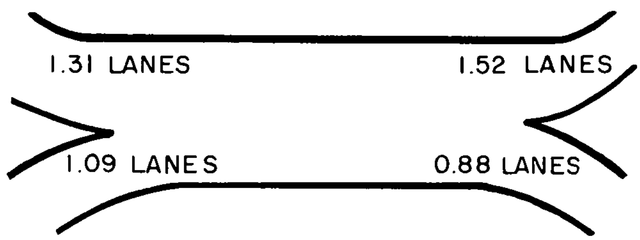
Figure E-12. Illustration of a section as the first step in solving an example major weave design problem.

2. For Input: 2 lanes and PHF = 0.91, $SV = 1{,}370$ pcphpl. Thus $N_{nw} = (1{,}400 + 800)/1{,}370 = 1.61$.
3. $W = (4 - 1.61) = 2.39$. This is a reasonable value. Go to step 5.
4. Does not apply in this case.
5. $W/N = 0.59$. From primary major weave equation of Table E-3,

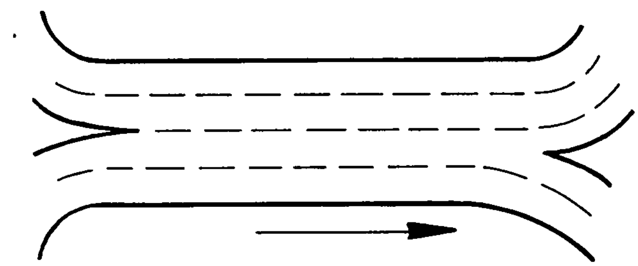
$$\begin{aligned}\log(0.59) &= -1.16 + 0.660\,(0.333)\\ &\quad -3.10\,(0.364)(\log 0.333)\, e^{-0.1L}\\ &\quad + 0.372 \log(50)\end{aligned}$$

so that $-0.229 = -1.16 + 0.220 + 0.538e^{-0.1L} + 0.632$ or $e^{-0.1L} = 0.147$. Thus, $L = 19.2$ (i.e., 1,920 ft).

Knowing $SV = 1{,}370$, one may estimate the input/output lanes required:



With the input/output lanes desired, there is no problem on the section boundaries. The design



realizes this and is recommended.

The same problem is solved graphically in Figures E-13 and E-14. The construction parallels that are outlined in the description:

- As illustrated in Figure E-13 (A), an $S_{nw} = 55$ reflected off the "Input: 2 lanes" curve yields $SV = 1{,}000$ pcphpl. Continuing to $V_{nw} = 2{,}200$ pcph and reflecting down, $N_{nw} = 2.2$. Pivoting through $N = 4$, $W = 1.8$. Dropping down to $N = 4$, $W/N = 0.45$.
- In Figure E-13 (B), a line drawn from W/N through VR (both known) is extended to T_1. A line from $S_{nw} =$ 55 through this T_1 value would intercept h at a negative value. However, h must be positive. Therefore, the assumption ($S_{nw} = 55$) yields an impossible situation. Abandon it.
- Try again for level of service C. Figure E-14 (A) yields $W/N = 0.59$. The first part of Figure E-14 (B) yields $h = 0.085$. In the second part, draw a line from R to VR. This intercepts T_2. Draw a line from $h = 0.085$ through T_2 to intercept L, and find $L \simeq 19.2$ (i.e., 1,920 ft).

This problem was adapted from Example 7.1 of the HCM. For the length determined herein, the HCM would have predicted a good (high) level of service B with a service volume of 945 pcphpl (equivalent). The equivalent service volume averaged for the recommended procedure may be computed from

$$SV_{\text{equiv}} = (1 - VR)\ SV + VR\ [V_w/W(\text{PHF})]$$

and is 1,082 pcphpl (equivalent). This is a useful index in comparing the two procedures.* Note that the HCM would have been more optimistic about the service being delivered, and would thus underdesign.

Example 2

A section is to be designed so that it may function at level of service B with the volumes as indicated in Figure E-15. There are 5 percent trucks, negligible grade. One may select both N and L.

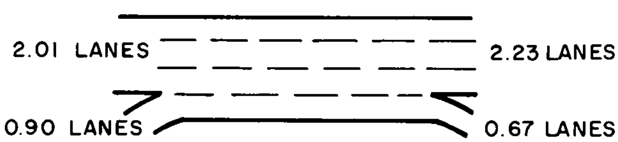
An attempt will be made to handle this as an auxiliary lane design. Based on the mainline output volume (2,480 vph, or $2{,}480 \times 1.05 = 2{,}605$ pcph), a three-lane mainline is desired.

The problem will be first solved according to the analytic procedure specified previously.

1. From Table E-2, $S_{nw} = 55$ mph.
2. From Figure E-4, for "Input: 3 lanes," $SV = 1{,}167$ pcphpl. Thus $N_{nw} = (1{,}765 + 210)/1{,}167 = 1.69$.
3. For $N = 4$, $W = 2.31$. This is essentially the maximum shown in Table E-1. It will be taken that the maximum *is* violated. Go to step 4.
4. Set $W = 2.3$. Thus $N_{nw} = 1.70$, resulting in a negligible difference in S_{nw}. This is found by $SV = (1{,}765 + 210)/1.70 = 1{,}162$. From Figure E-4, $S_{nw} = 55$ mph.
5. Note that with W at its maximum, added length affects only ΔS without influencing S_{nw}. From the primary ramp-weave equation of Table E-3, desiring $\Delta S = 0$ implies $L = 21.3$. This is outside the calibrated and feasible range. Note that for $L = 20$, $\Delta S = 0.6$. One concludes that for $L = 20$, the nonweaving traffic will operate at level of service B, while the weaving traffic will operate closer to mid-C.
6. Does not apply in this case.

The same problem is solved graphically in Figure E-16. The construction parallels that outlined in the description.

In the graphical solution, it appears that W is just at its limit of 2.3. If the designer proceeded to the nomograph with this in mind, $\Delta S \cong 7$ mph with $L = 1{,}070$ ft. The designer should realize that if L is increased (dashed line in Fig. E-16), the W thus implied could not be delivered—thus N_{nw} remains constant, S_{nw} does not change, and the left side of the nomograph does not apply. $L = 20$, $\Delta S \simeq 0.5$ from the nomograph. One may verify at $SV = 1{,}070$ ft that the following lanes are required:



* Caution must be used. In the HCM, quality of flow and not the computed SV determines level of service when $k = 3$.

At this point, a cautious designer might attempt a design for a two-lane mainline. He would find that the output mainline would operate at level of service C. This will have to be considered in conjunction with the internal service provided.

The example as first stated is an adaptation of Example 7.3 of the HCM. The approach used therein (on/off pair without auxiliary lane) would not be handled by the procedure developed herein. Rather, Chapter 8 ("Ramps") of the HCM would be recommended for that approach.

For the solution as stated herein ($L = 20$), Chapter 7 of the HCM would predict $k = 2.7$, quality of flow II, $SV = 1{,}093$ pcph. This implies level of service B.

Example 3

Consider Example 2 with 500 vph (5 percent trucks) added to the mainline traffic. Design for level of service B, if possible.

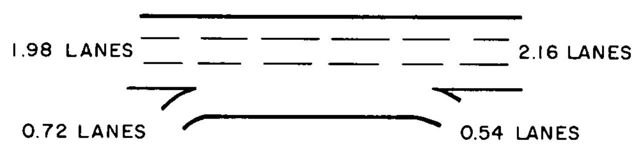
This changes the mainline flow to 2,289 pcph. Based on input/output volumes, a three-lane mainline is still recommended. Note that $VR = (V_w/V_{TOT}) = 0.36$.

This problem can be solved by graphic techniques.

As shown in Figure E-17 (A), level of service B (nonweaving) leads to $W \simeq 1.88$ or $W/N \simeq 0.475$. From Figure E-17 (B), the ΔS and the L thus implied are ridiculous. Physically, the section is being kept short to contain the weaving vehicles, to the benefit of the through traffic. Operationally, this is poor design.

The dashed lines 1 and 2 on the same figure show the design for level of service C (nonweaving). A PHF = 0.91 is assumed. It happens that $W = 2.3$ exactly, so that the left portion of the nomograph need not apply. If it did, $\Delta S \simeq 0$ mph with $L \simeq 1{,}630$ ft. Line 3 shows another possibility.

For either case, $SV = 1{,}450$ pcphpl. The lanes required are, therefore,



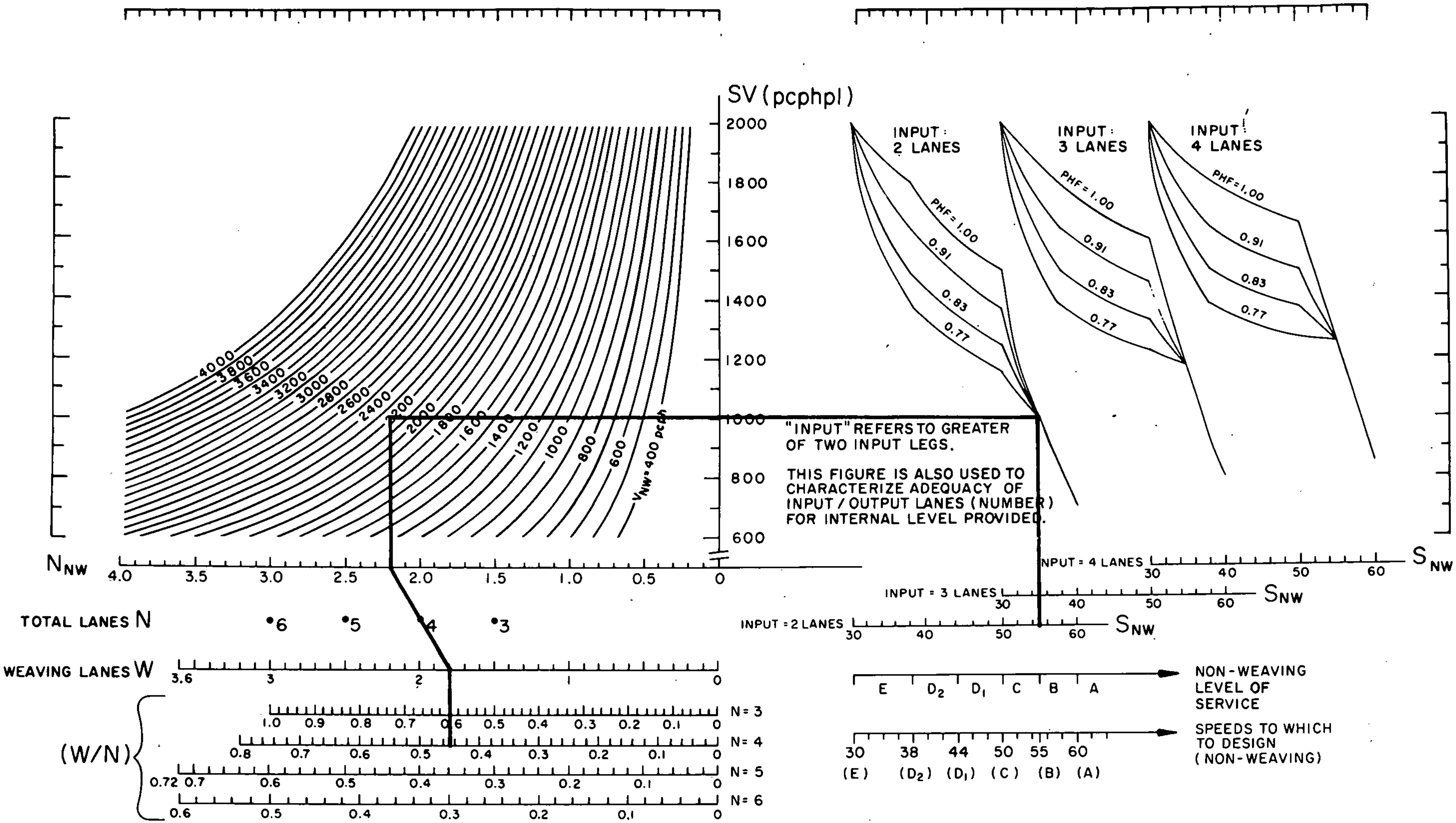
The problem is completed.

Note that, in accordance with HCM practices, the design level (speed and service volume) is realized only during the peak 5 min of the hour under consideration. At other times, the level(s) of service is (are) better.

ANALYSIS

Analysis problems are those problems in which N, L, configuration, and volumes are known, and it is desired to assess the operation of the section. All evaluations of existing sections fall into this classification.

In addition, it is sometimes most effective to do design by evaluating a range of feasible lengths and widths. In this



(A) At level of service B

Figure E-13. Attempt to solve by the graphic technique the major weave design problem posed in Example 1 at levels of service B and C.

way, one may assess the impact of an additional 500 ft or an additional lane. This is, in fact, handled as a set of analysis problems.

The analysis approach is best handled by the graphic solution or the computer program. The analytic solution is as straightforward as the graphic, but is more burdensome computationally.

The essence of the analysis procedure is:

- Assume an S_{nw} and determine the W/N thus implied from Figure E-6 for major weaves and Figure E-11 for ramp weaves.
- For the W/N, determine the S_{nw} as computed from Figure E-8 for major weaves * and Figure E-10 for ramp weaves.
- If the S_{nw} determined in the second step is not the same as that assumed, adjust the assumed one in the direction of the actual one and solve again. Continue until a solution is reached.

In practice, two or three iterations will determine the solution once the analyst has some experience.

The procedure is illustrated in the section immediately following.

* The "h" in Figure E-8 nomograph is found from Figure E-7 nomograph once (at the beginning of the problem).

ANALYSIS PROBLEMS

Example 1

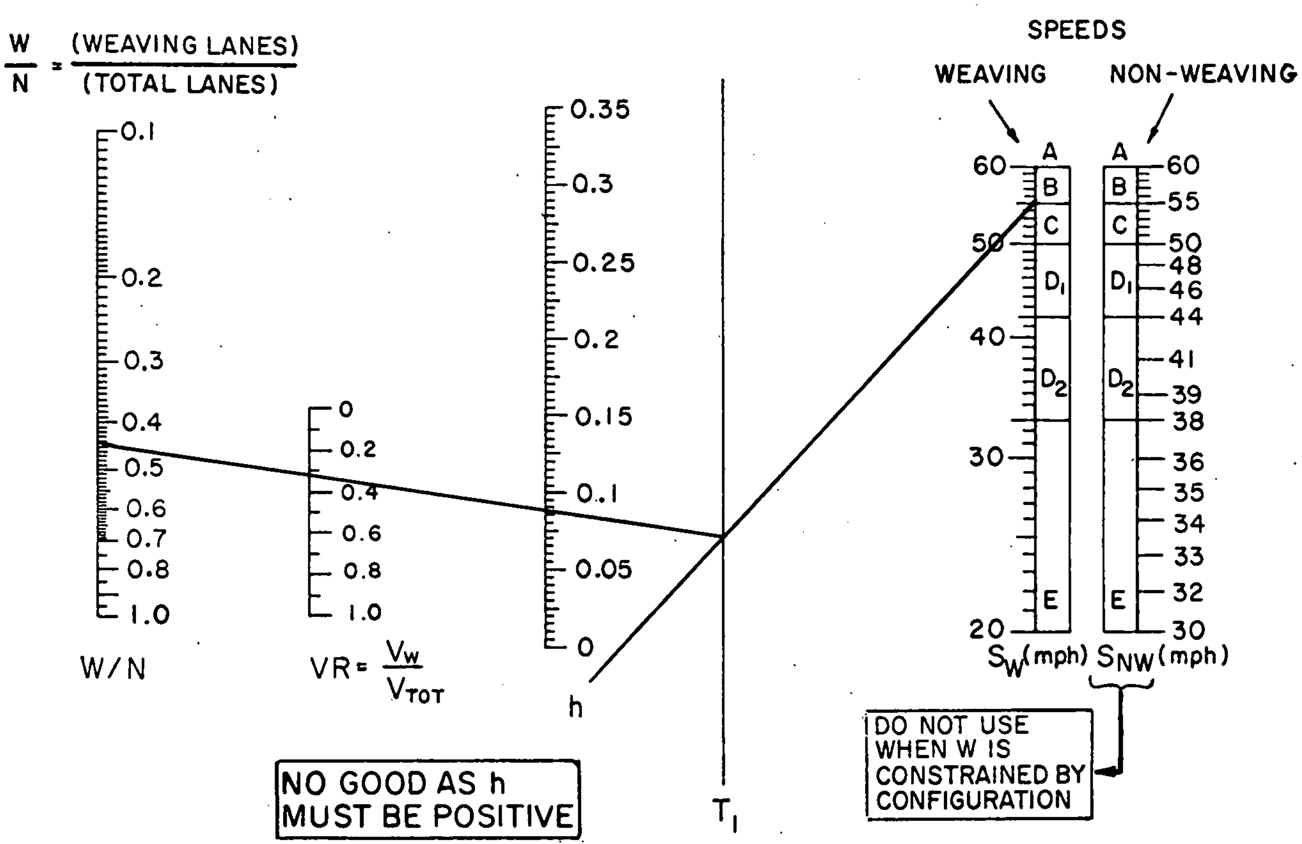
This is to be a design problem in that configuration is not fully specified. Configuration is to be designed so as to be adequate for the solution reached.

Consider the flows shown in Figure E-18, already converted to pcph. The PHF is 1.00. Assess the level(s) of service provided for combinations of N and L where $N = 3$, 4, 5 and $L = 5$, 10, 15, 20. Specify W-values for each case so that adequate configurations can be laid out. Note that the volumes indicate the configuration to be a major weave.

Before beginning, note that inspection of Figure E-18 and N leads one to assume certain line drawings of configuration as illustrated in Figure E-19. These will be used in the analysis only to determine "Input Lanes (Greater)" as used in Figure E-6.

Note that $R = 0.33$, $VR = 0.45$, and $V_{nw} = 2{,}750$. To illustrate the analysis procedure, a complete solution will be done for $L = 10$ and $N = 4$, which is representative of the analysis situations commonly encountered.

- Note that for a major weave, Figures E-6, E-7, and E-8 are to be used. The first task is to find h from Nomograph 2 in Figure E-8. The solution is shown in Figure



(B) At level of service C

Figure E-13. Continued.

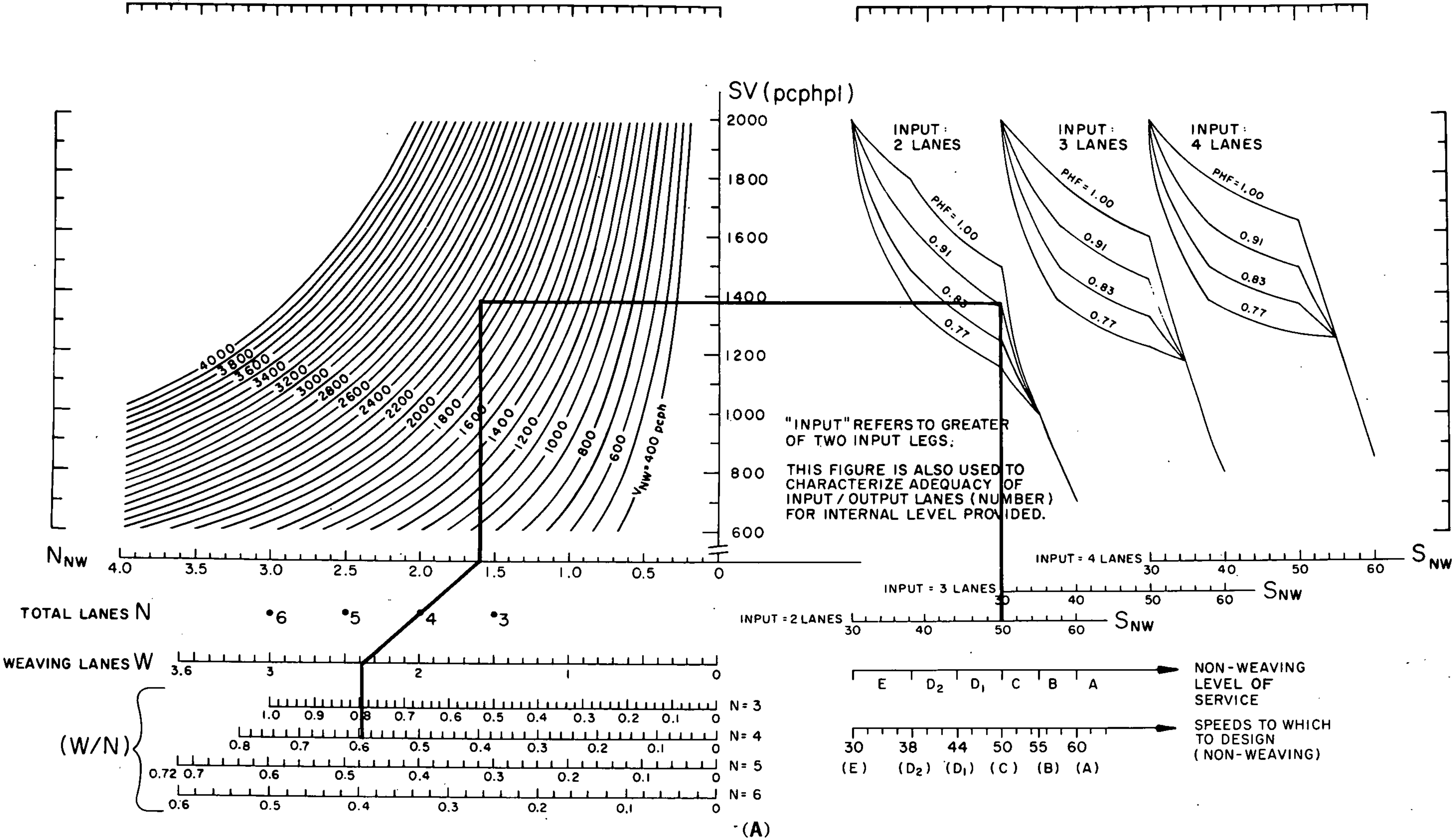
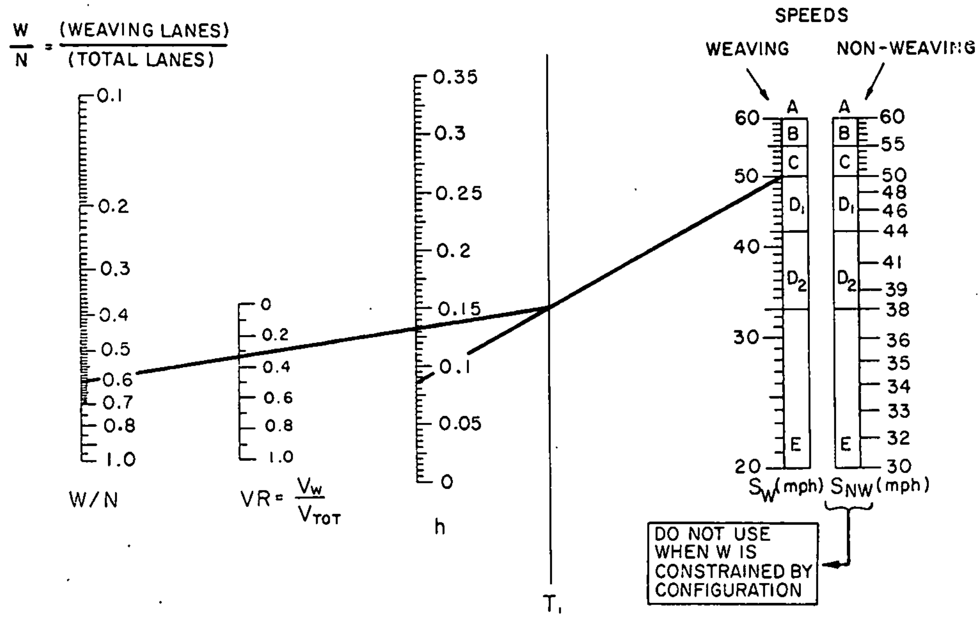
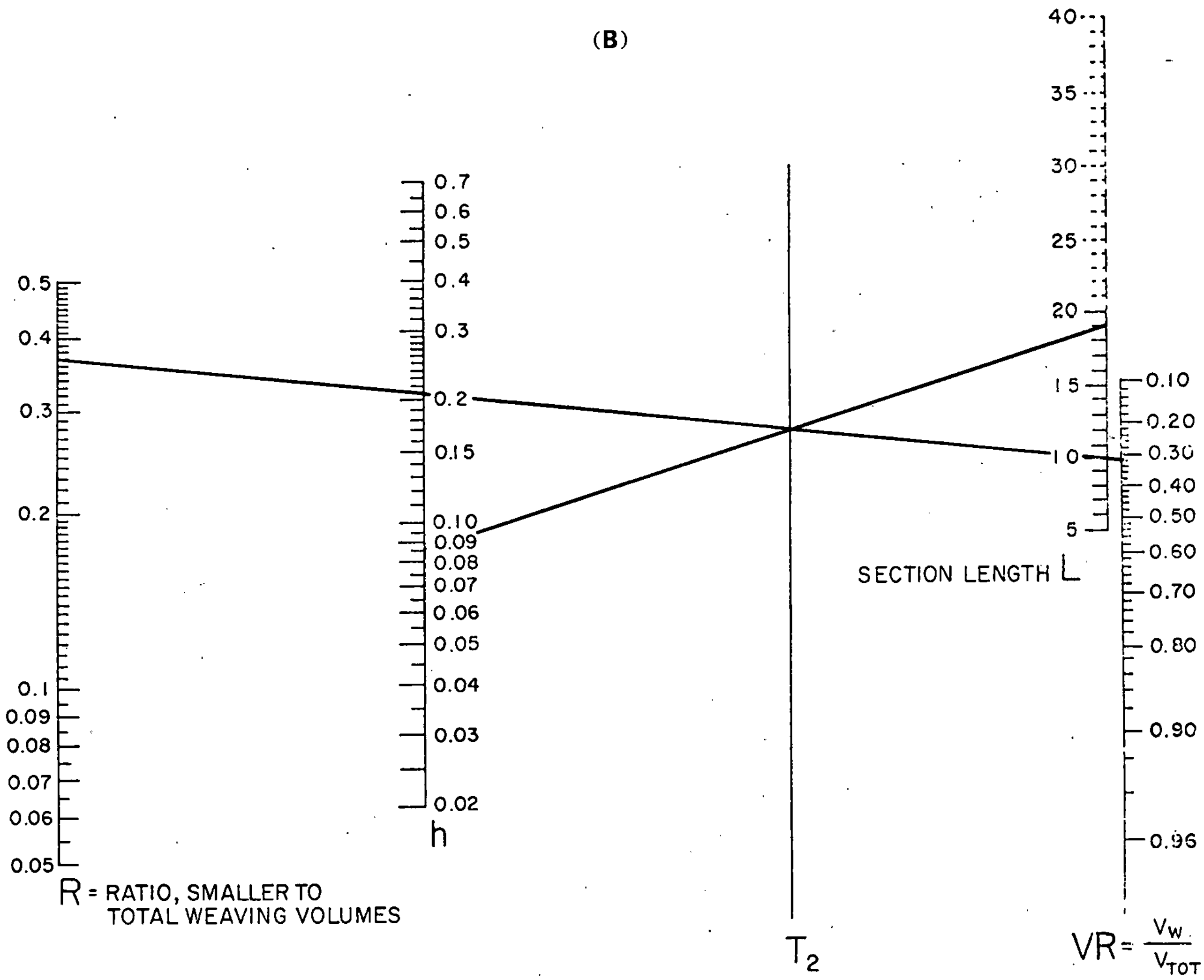


Figure E-14. Attempt to solve by the graphic technique the major weave design problem posed in Example 1 at level of service C.



Using Nomograph 1 (Fig. E-7)

(B)



Using Nomograph 2 (Fig. E-8)

Figure E-14. Continued.

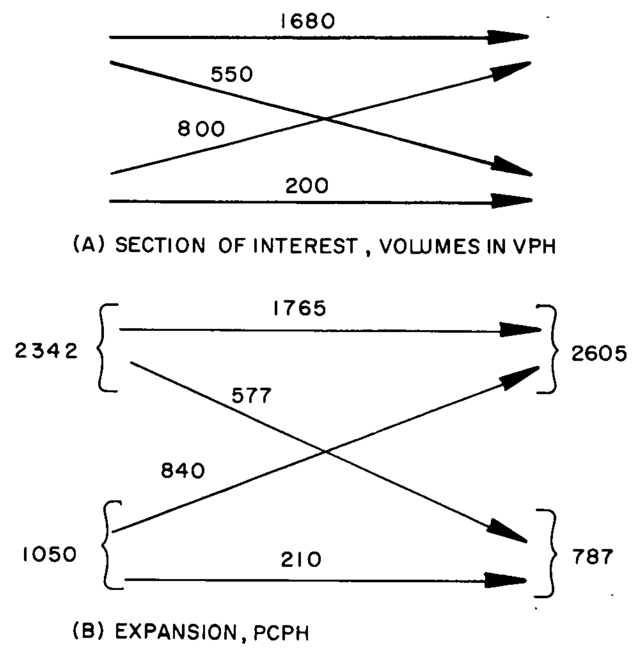


Figure E-15. Illustration of a ramp-weave section design problem (see Example 2).

E-20. The line marked "first this" is drawn from R to VR, thus intercepting T_2. "Then this" is drawn from L through this T_2 point and extended to find $h = 0.133$.

- Assume $S_{nw} = 50$ and begin analysis as indicated in Figure E-21. W/N is found in (A); the S_{nw} that results in (B) via the two lines shown ("first this" from W/N through VR to T_1, "then this" from h through T_1 to S_w) indicates the original assumption was very poor. The assumption of $S_{nw} = 40$ is not much better, as indicated in (C) and (D). An assumption of $S_{nw} = 35$ results in $S_{nw} = 34$ [see (E) and (F)]. On the same figures, $S_{nw} = 34\frac{1}{2}$.

One may conclude that $S_{nw} \simeq 34$ mph with $S_w \simeq 26$ to 27 mph. These imply levels of service E for both flows. The W required is 2.5 lanes. *One must always return to the actual configuration to make sure that the W can be handled,* particularly if there is *no* through lane or if the heavier weaving flow does not have a through lane.

Note that if a person were doing several analysis problems with these volumes, he would have made a much better estimate of the starting point. For instance, when he went to $L = 15$ and $N = 4$, he would not assume $S_{nw} = 50$.

The results are summarized in Table E-4 for the several cases of interest in this example. Table E-5 is a blank copy of this form, which may be of use to the reader.

Table E-4 also indicates the "ideal" that would exist if there were no weaving with the total volume as given. This is based on $SV = V_{TOT}/N$ and level of service as read from the ramp-weave portion of Table E-3 in conjunction with Figure E-5. (The right-hand portion of Figure E-6 can be used to replace these two.)

Note from item 4 of Table E-4 that $N = 3$ would be a poor choice, and only $N = 5$ and $L = 20$ is really acceptable. Further, to achieve the same level that $L = 10$ and $N = 5$ yields, it is necessary to have $L = 15$ when $N = 4$.

Example 2

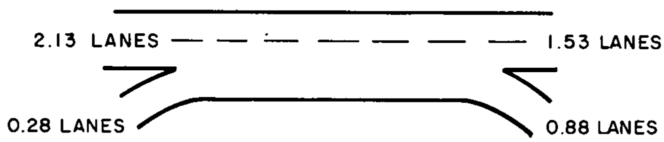
Consider the ramp-weave situation shown in Figure E-22. Evaluate the operation.

This analysis requires use of Figures E-10 and E-11.

Note that $VR = 0.427$ and $V_{nw} = 1{,}410$ pcph.

The solution is given in Figure E-23 (A) and (B). In (A), the assumption is made that $S_{nw} = 50$ mph. Pursuing this in (B), the S_{nw} implied is 54 mph or so. Assuming $S_{nw} = 54$ mph in the second attempt [dashed in (A)], the S_{nw} implied as found in (B)—dashed also—is about 54 mph. Note that, for ramp weaves, one may effectively use the S_{nw} value implied (or slightly more) as the new assumed S_{nw}.

The solution is therefore that $S_{nw} = 54$ mph and $S_w \simeq 38\frac{1}{2}$ mph. These imply levels of service C (almost B) and D for the nonweaving and weaving traffic, respectively. The 70 pcph ramp-to-ramp flow will be controlled by the weaving service provided. The lanes required for a $SV \simeq 1{,}020$ pcph are



so that the input mainline will be slightly constrained.

Note that neither of the two analysis problems required consideration of a constrained W. If they had, the analysis actually would have been simpler.

Example 3

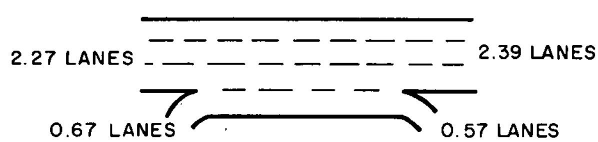
Consider the ramp-weave situation shown in Figure E-24. Evaluate the operation.

This analysis requires use of Figures E-10 and E-11 (Nomograph 3).

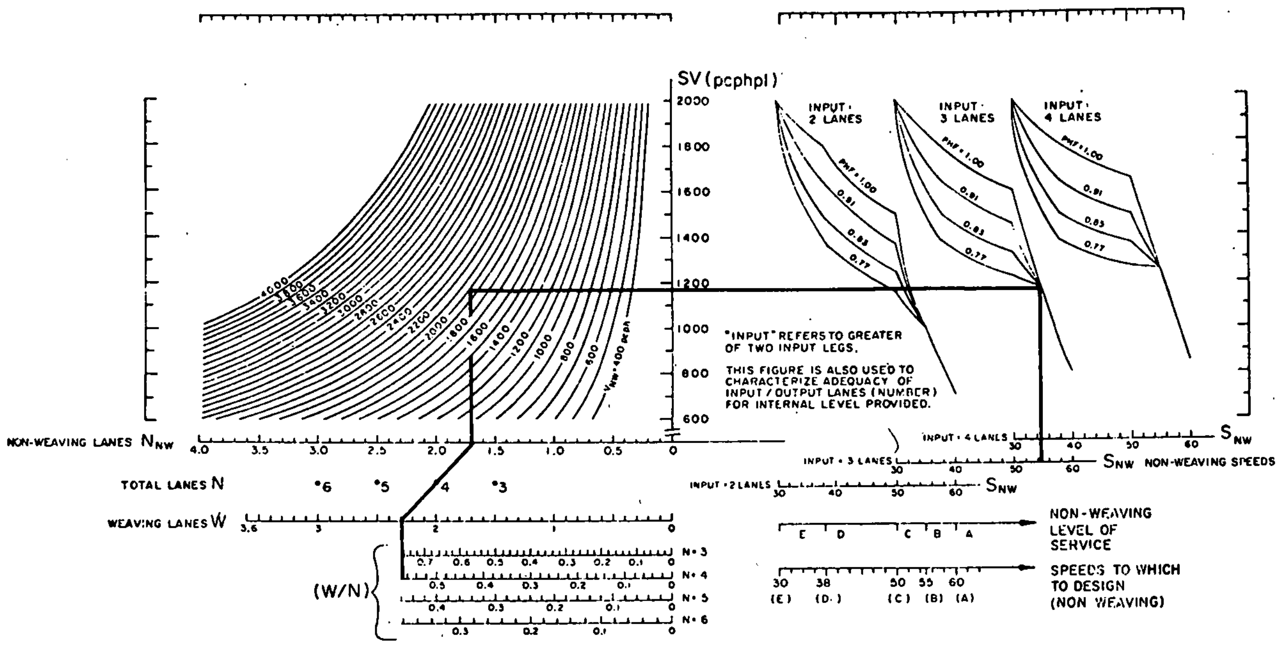
Note that $VR = 0.423$ and $V_{nw} = 1{,}500$ pcph.

The solution is given in Figure E-25. It is assumed that $S_{nw} = 50$. The fact that the W/N thus implied cannot be found in Figure E-10 is a clear indication that the W that would result exceeds the configurational limit of 2.3. Therefore, W is taken as 2.3 and the S_{nw} is found to be 58 mph [Fig. E-25 (B)]. From (A) of the same figure (dashed line), $\Delta S \simeq 5\frac{1}{2}$ mph so that $S_w \simeq 52\frac{1}{2}$ mph. This yields levels of service B (almost A) and C for nonweaving and weaving traffic, respectively. The weaving width W is constrained.

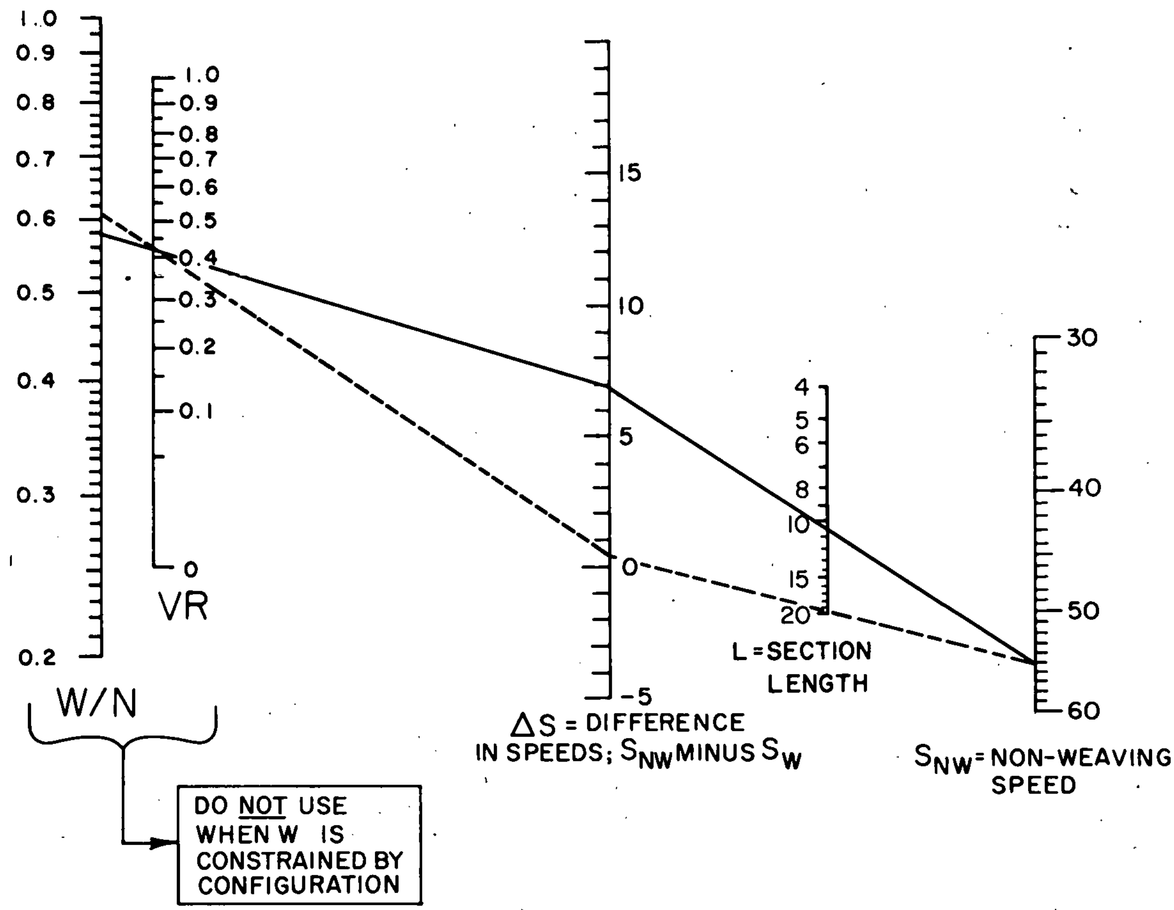
The lanes required for $SV \simeq 880$ pcph are



which are adequate in all cases.

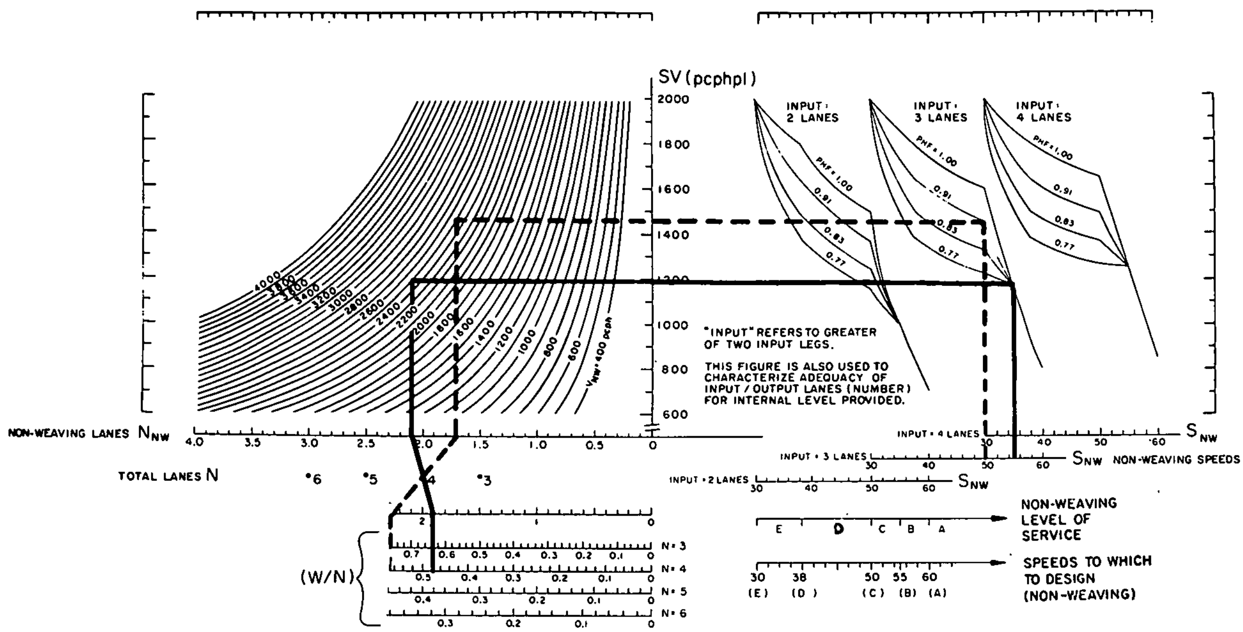


(A) Using Fig. E-10.

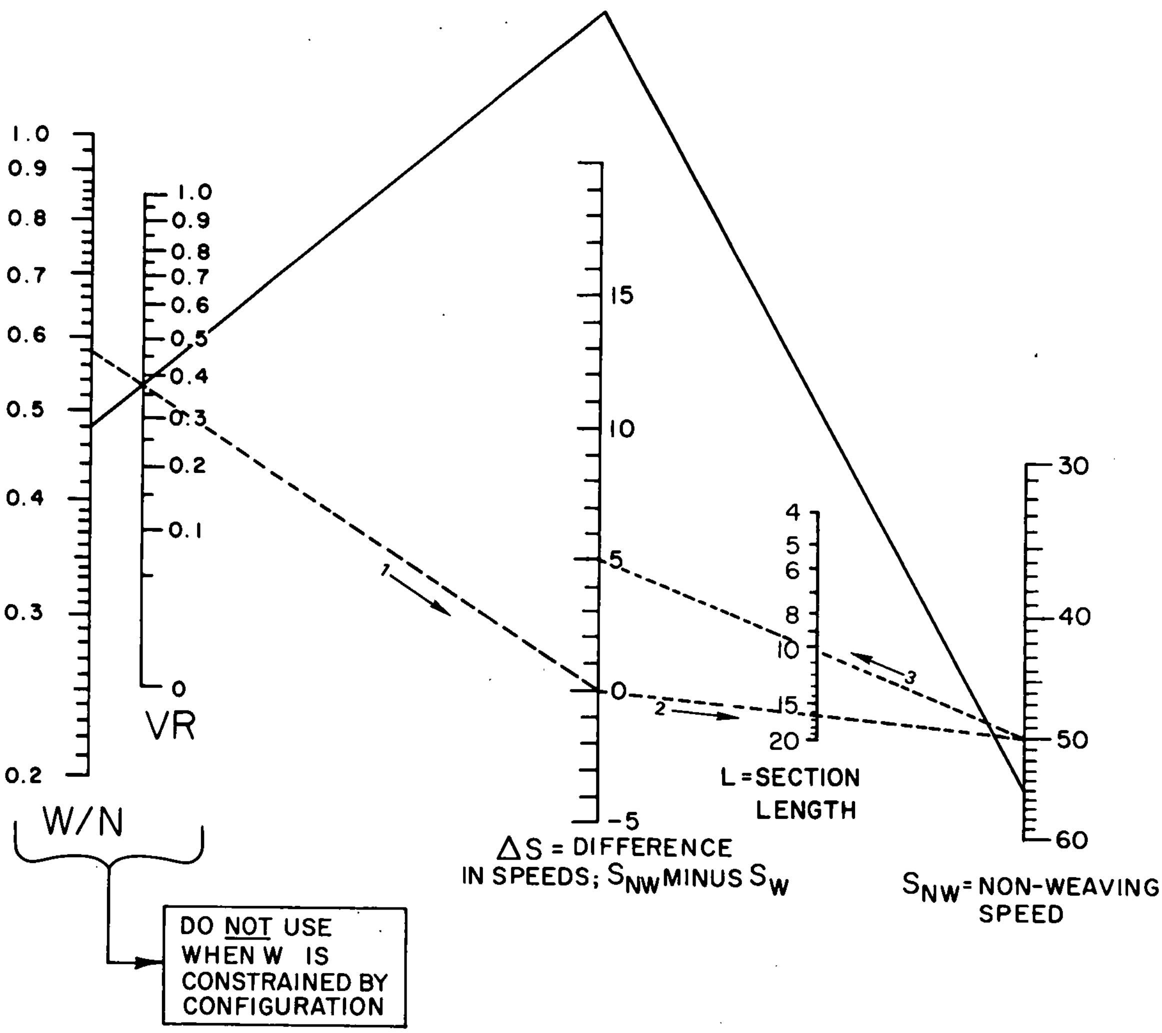


(B) Using Nomograph 3 (Fig. E-11).

Figure E-16. Attempt to solve by the graphic technique the ramp-weave design problem posed in Example 2 at level of service B.



(A) Using Fig. E-10.



(B) Using Nomograph 3 (Fig. E-11).

Figure E-17. Attempt to solve by the graphic technique the ramp -weave design problem posed in Example 3 at level of service B.

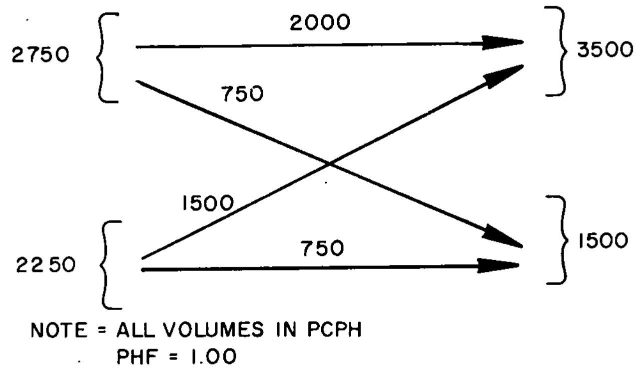


Figure E-18. Illustration of weaving section flows to determine area configuration for Example 1 analysis problem.

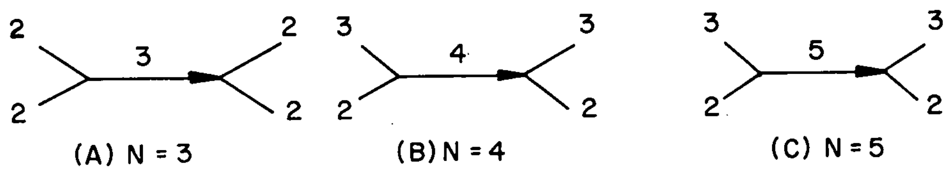


Figure E-19. Line drawings of assumed configurations that are used in solving the Example 1 analysis problem.

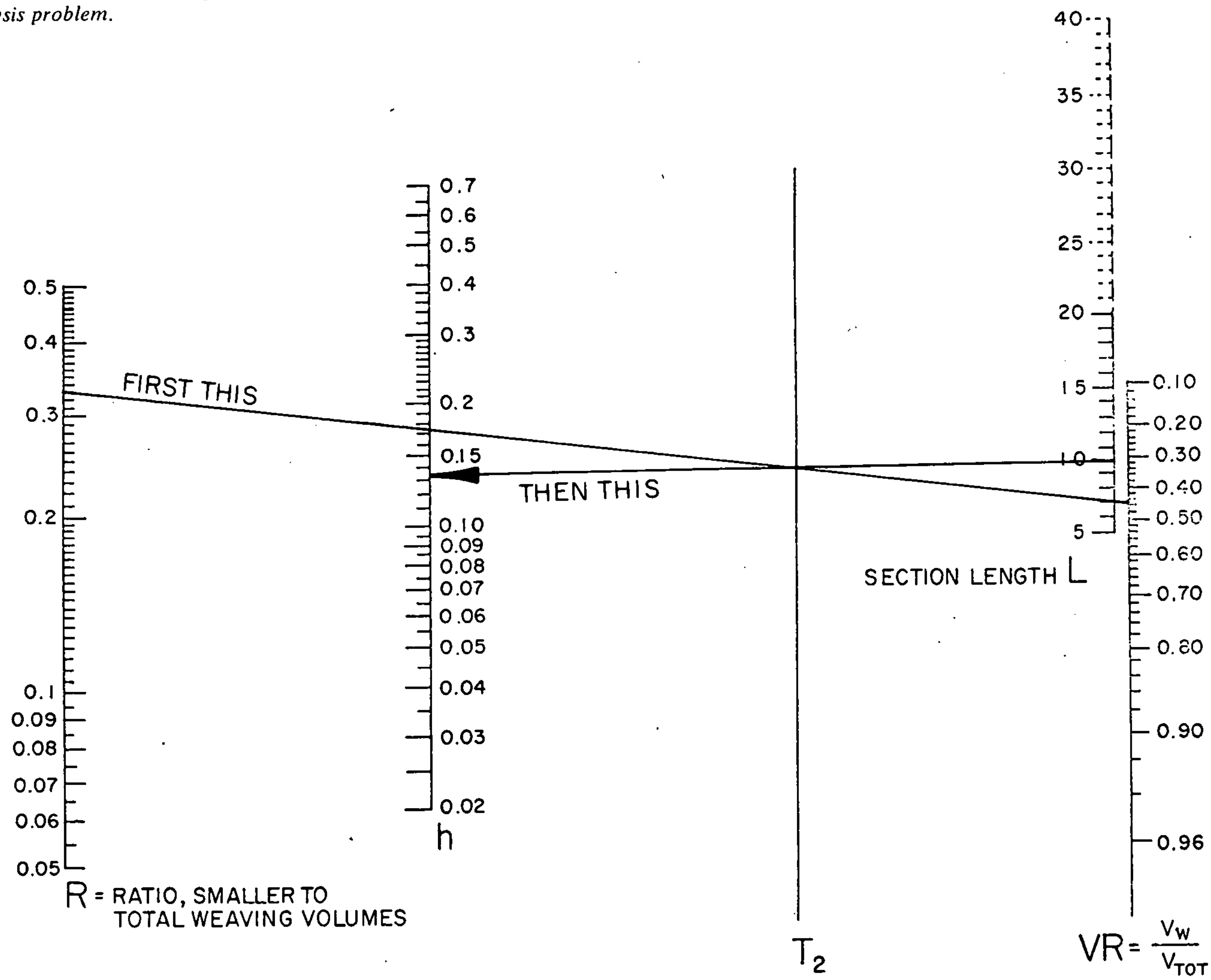
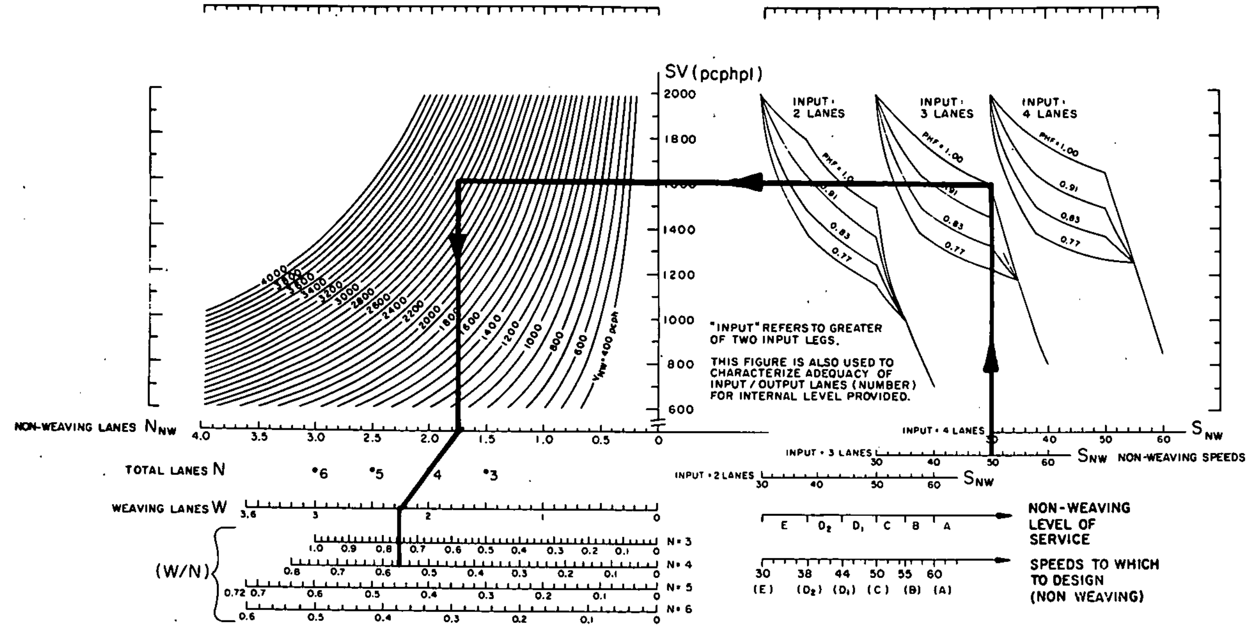
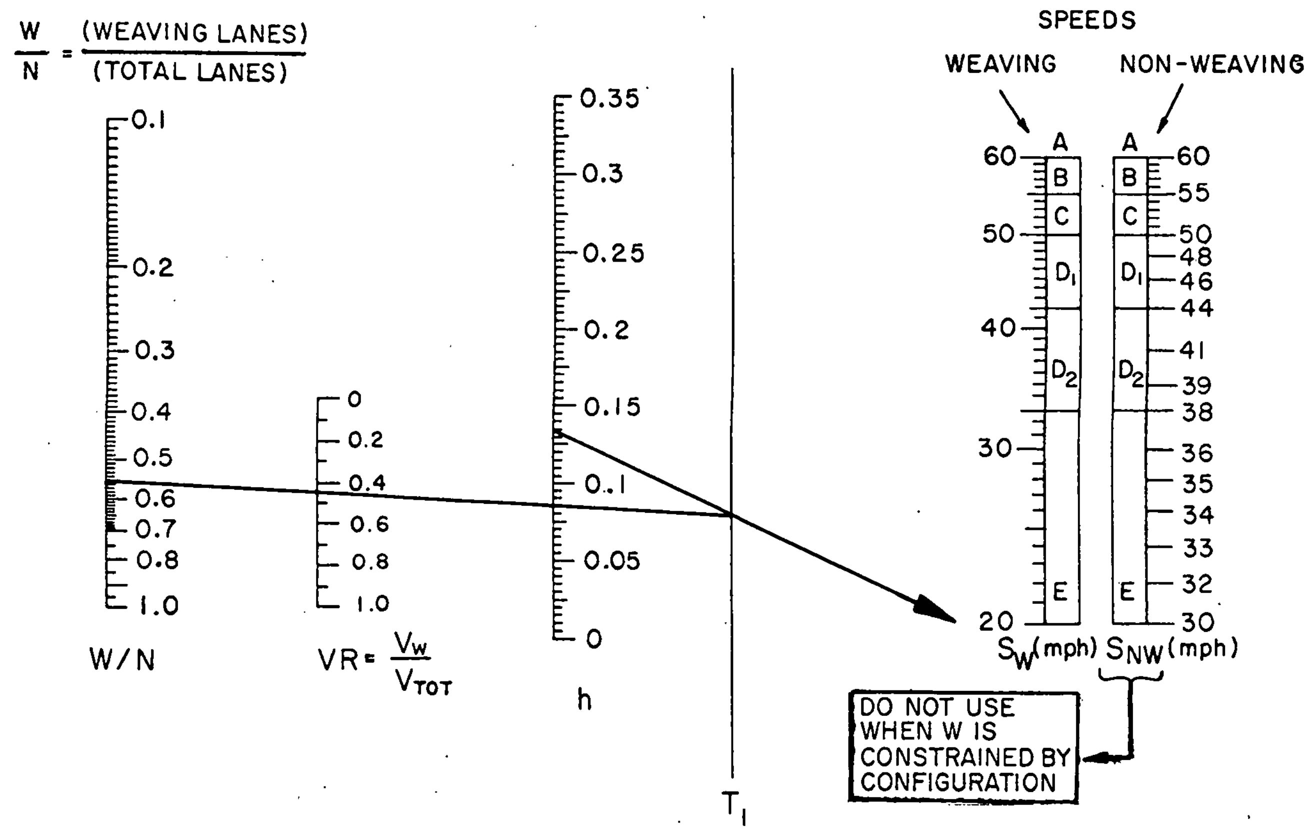


Figure E-20. Use of Nomograph 2 to solve Example 1 analysis problem.

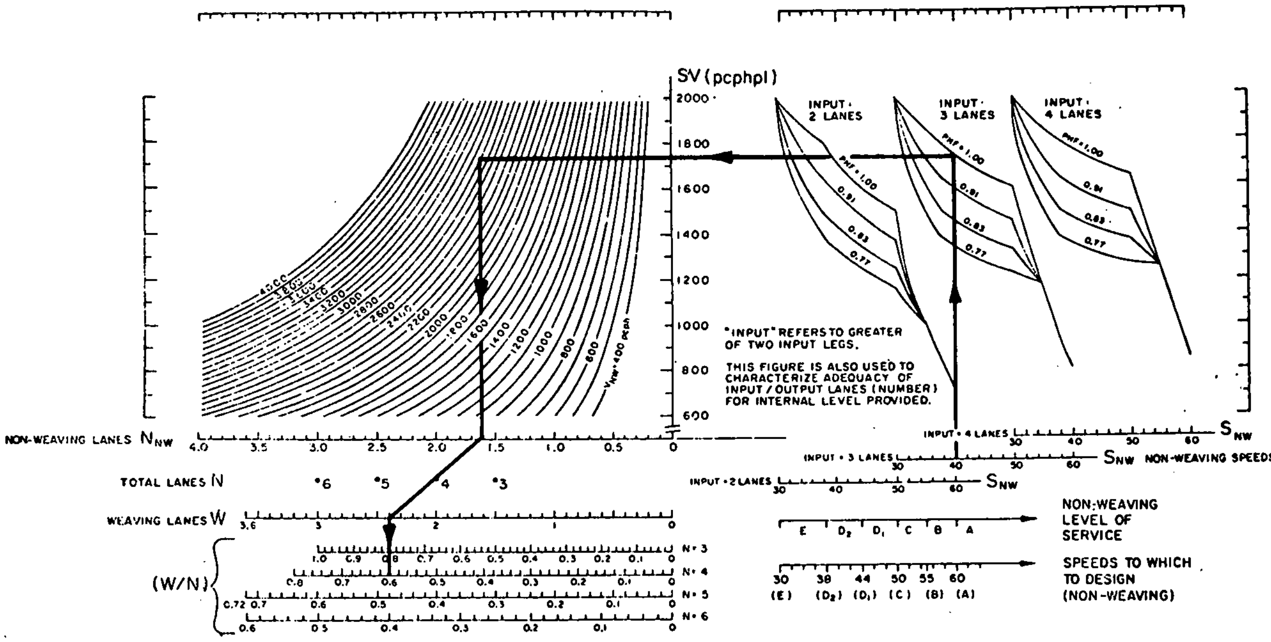


(**A**) Assume $S_{nw} = 50$ and determine W/N.

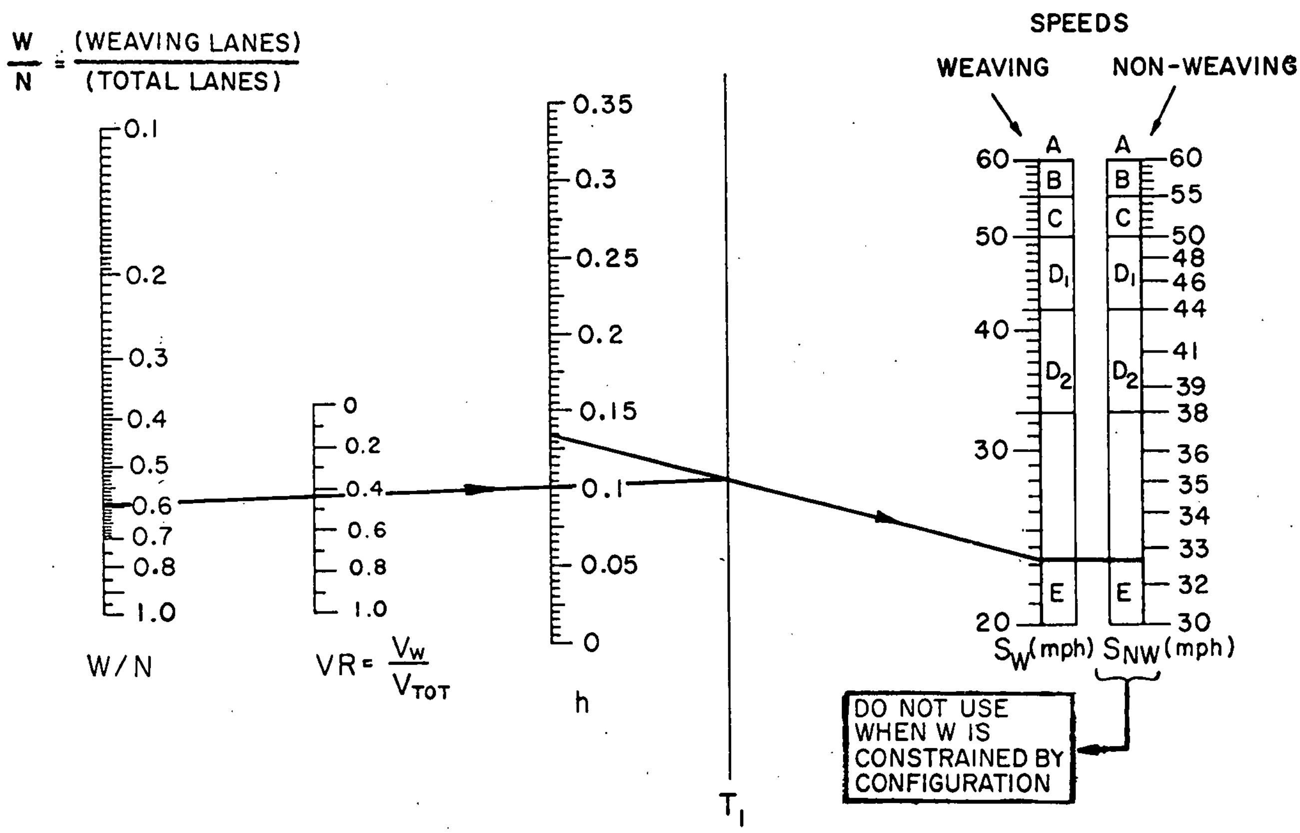


(**B**) Using the W/N value implied in (A), determine S_w and S_{nw}.

Figure E-21. Steps toward solving Example 1 analysis problem.

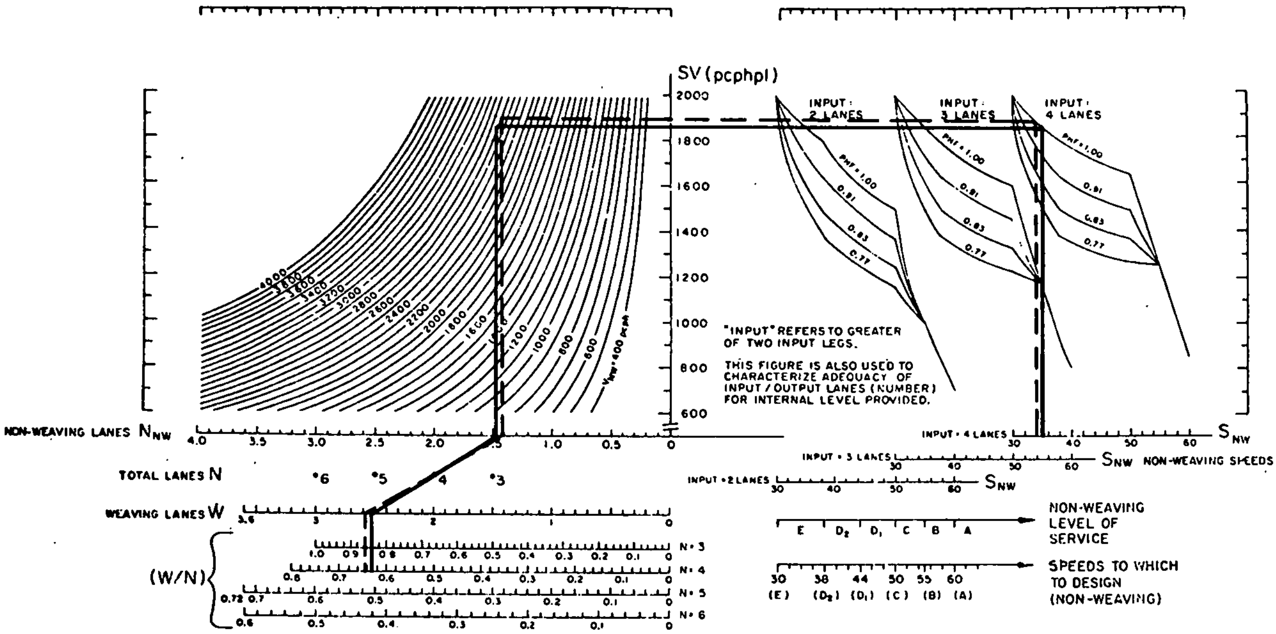


(C) In view of unsatisfactory results in (A) and (B), assume $S_{nw}=40$ and begin again.

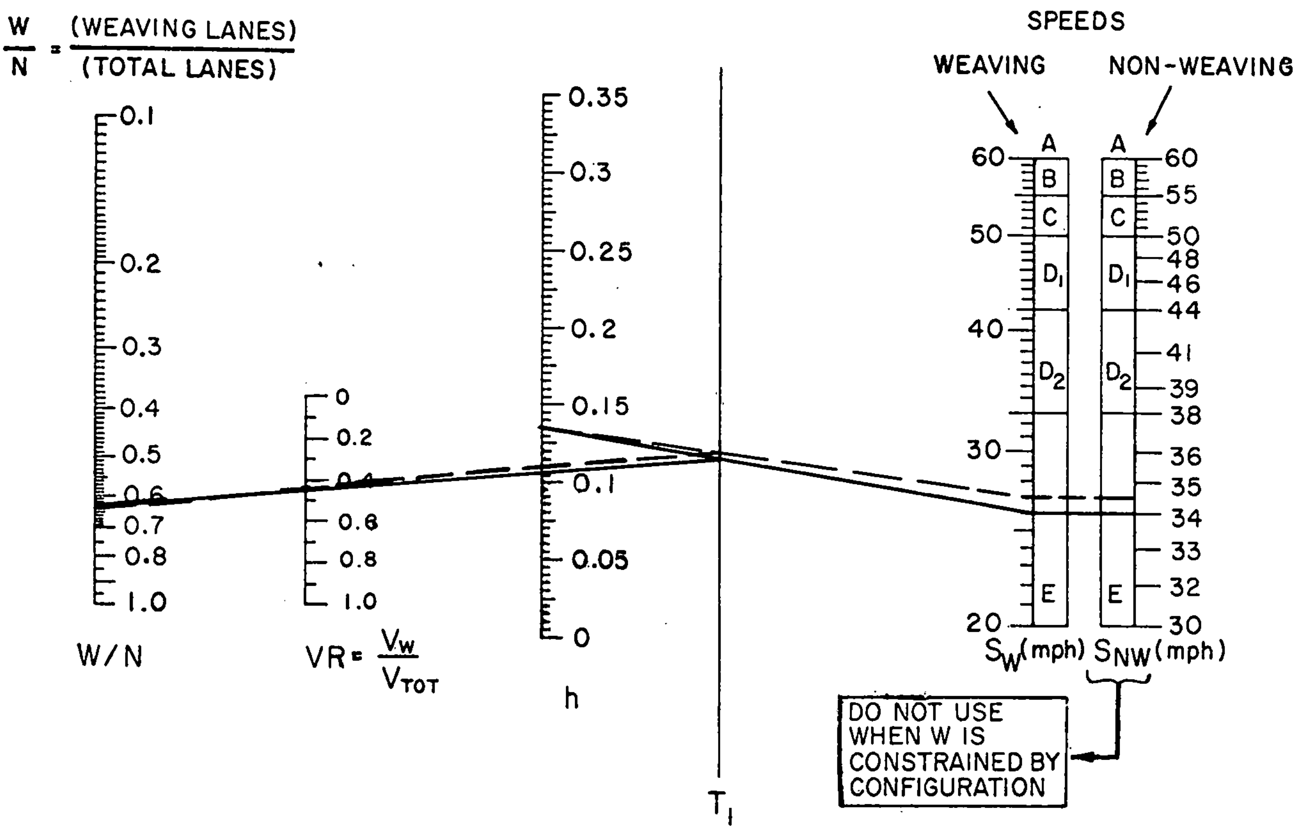


(D) Determine new S_w and S_{nw}.

Figure E-21. Continued.



(E) Begin again, assuming $S_{nw}=35$ (solid line) and $S_{nw}=34$ (broken line), determine corresponding values for W/N.



(F) Determine S_{nw} values that correspond to the W/N values obtained in (E).

Figure E-21. Continued.

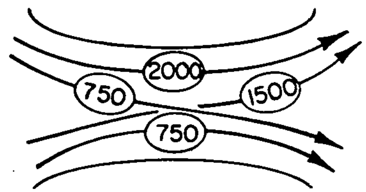
TABLE E-4

SUMMARY OF ANALYSIS RESULTS FOR EXAMPLE 1

1. WIDTHS W NEEDED

L \ N	3	4	5
5	1.6	2.6	3.6
7.5			
10	1.6	2.5	3.5
12.5			
15	1.6	2.5	3.4
17.5			
20	1.5	2.4	3.3

2. SITE DESCRIPTION



A. MAJOR ☐ OR RAMP-WEAVE ☐

B. PCPH ☐ OR VPH ☐ (ABOVE)
● TRUCKS ____%
● GRADE ____%
____ MI. LONG
● LANE WIDTH ____ FT.

PHF = 1.00; CORRECTION NOT SHOWN ABOVE

C. VR = 0.45 ; R = 0.333

4. SUMMARY BY SPEED (NON WEAVE / WEAVE)

L \ N	3	4	5
5	30 / 10	30 / 18	30 / 22
7.5			
10	30 / 18	34 / 27	39 / 34
12.5			
15	32 / 23	39 / 34	45 / 43
17.5			
20	34 / 26	42 / 39	50 / 50
	41	53	55

NON WEAVE / WEAVE

5. SUMMARY BY LEVEL OF SERVICE (NON WEAVE / WEAVE)

L \ N	3	4	5
5	E / F	E / F	E / E
7.5			
10	E / F	E / E	D_2 / D_2
12.5			
15	E / F	D_2 / D_2	D_1 / D_1
17.5			
20	E / E	D_2 / D_2	D_1 / D_1
	D_2	C	B

SITUATION ON OPEN FREEWAY AT VOLUME GIVEN

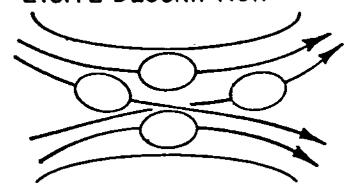
TABLE E-5

SUMMARY OF ANALYSIS RESULTS SUITABLE FOR DESIGN DECISIONS

1. WIDTHS W NEEDED

L \ N	3	4	5
5			
7.5			
10			
12.5			
15			
17.5			
20			

2. SITE DESCRIPTION



A. MAJOR ☐ OR RAMP-WEAVE ☐

B. PCPH ☐ OR VPH ☐ (ABOVE)
● TRUCKS ____%
● GRADE ____%
____ MI. LONG
● LANE WIDTH ____ FT.

PHF = ____; CORRECTION NOT SHOWN ABOVE

C. VR = 0.____ ; R = 0.____

4. SUMMARY BY SPEED (NON WEAVE / WEAVE)

L \ N	3	4	5
5			
7.5			
10			
12.5			
15			
17.5			
20			

NON WEAVE / WEAVE

5. SUMMARY BY LEVEL OF SERVICE (NON WEAVE / WEAVE)

L \ N	3	4	5
5			
7.5			
10			
12.5			
15			
17.5			
20			

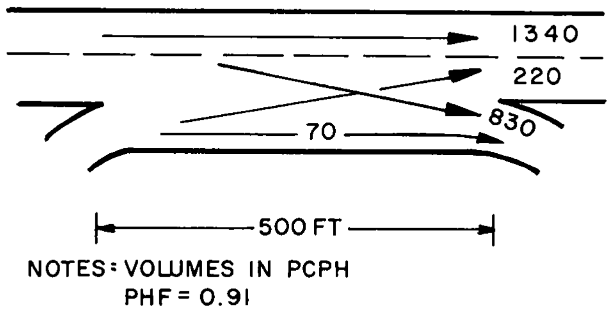
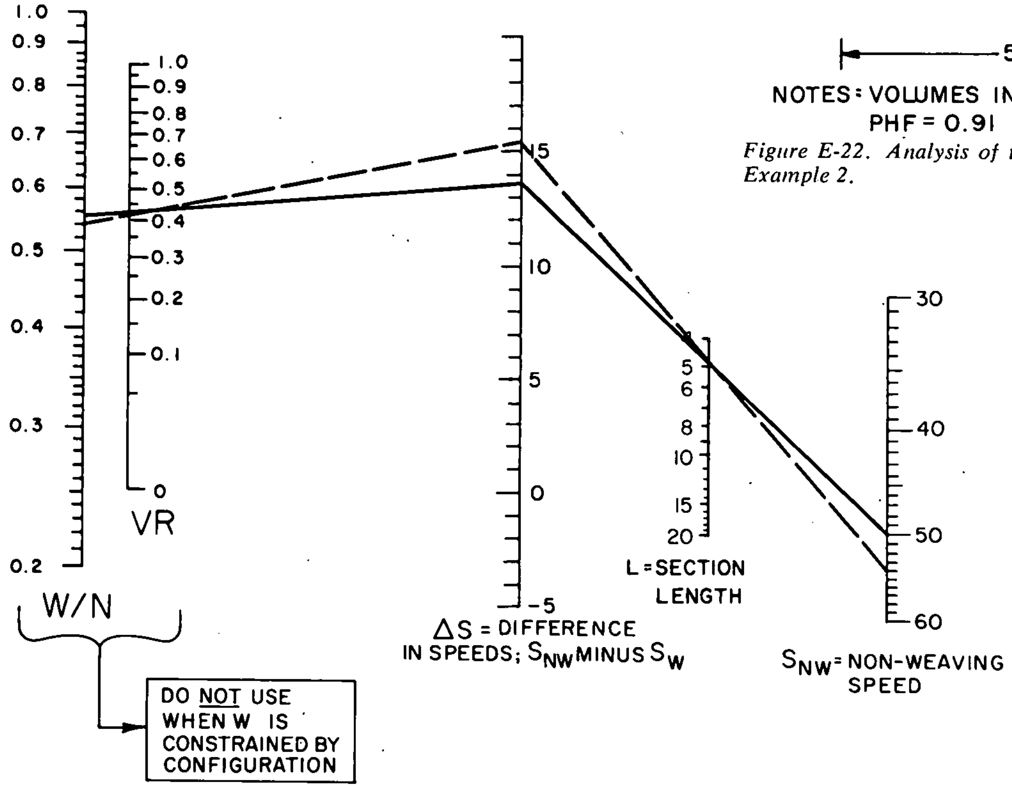
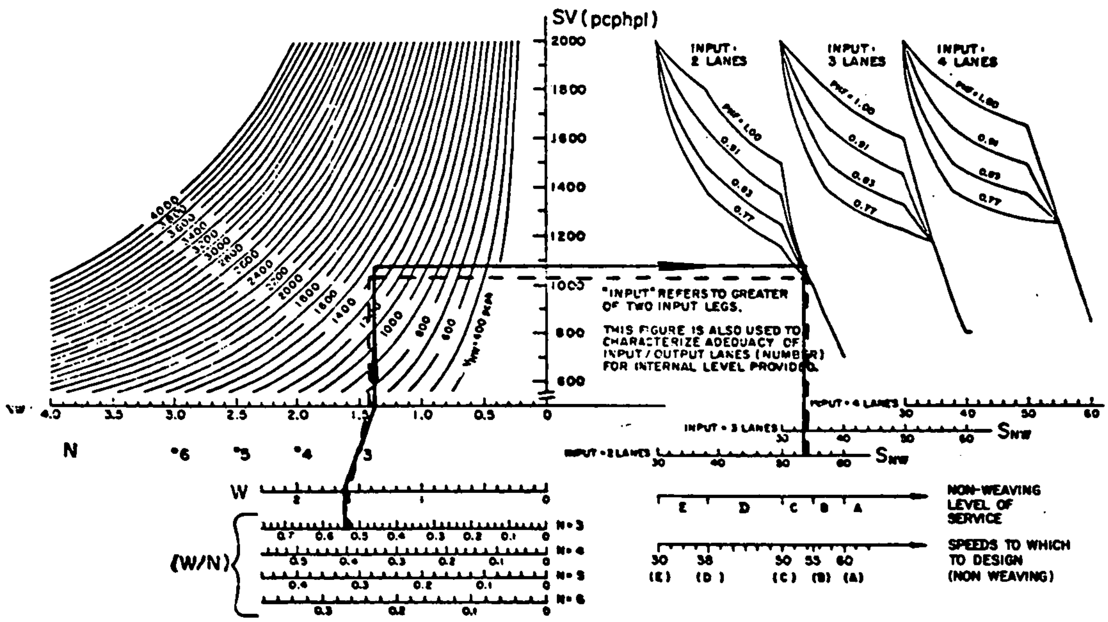


Figure E-22. Analysis of the ramp-weave problem posed in Example 2.



(A) Assume, for the first trial, $S_{nw}=50$ (solid line), and, for the second trial, $S_{nw}=54$ (broken line); determine corresponding values for W/N.



(B) Determine S_{nw} values that correspond to the W/N values obtained in (A).

Figure E-23. Solution to the ramp-weave section analysis problem in Example 2.

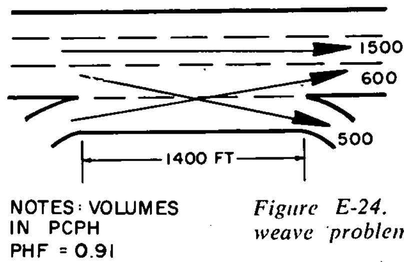
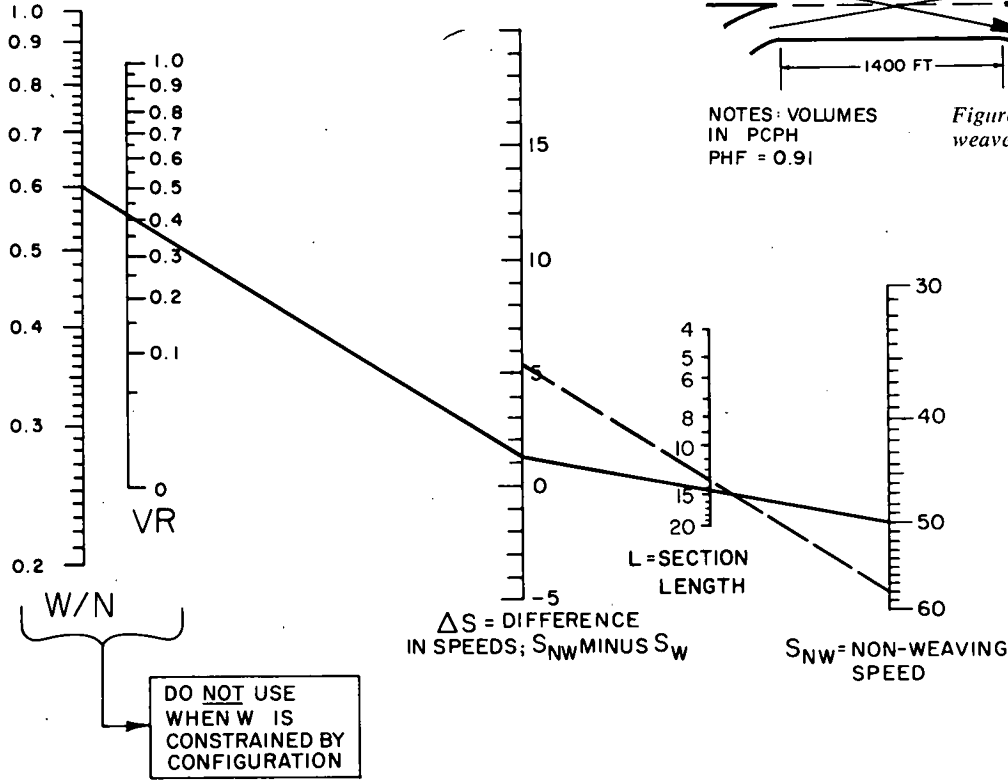
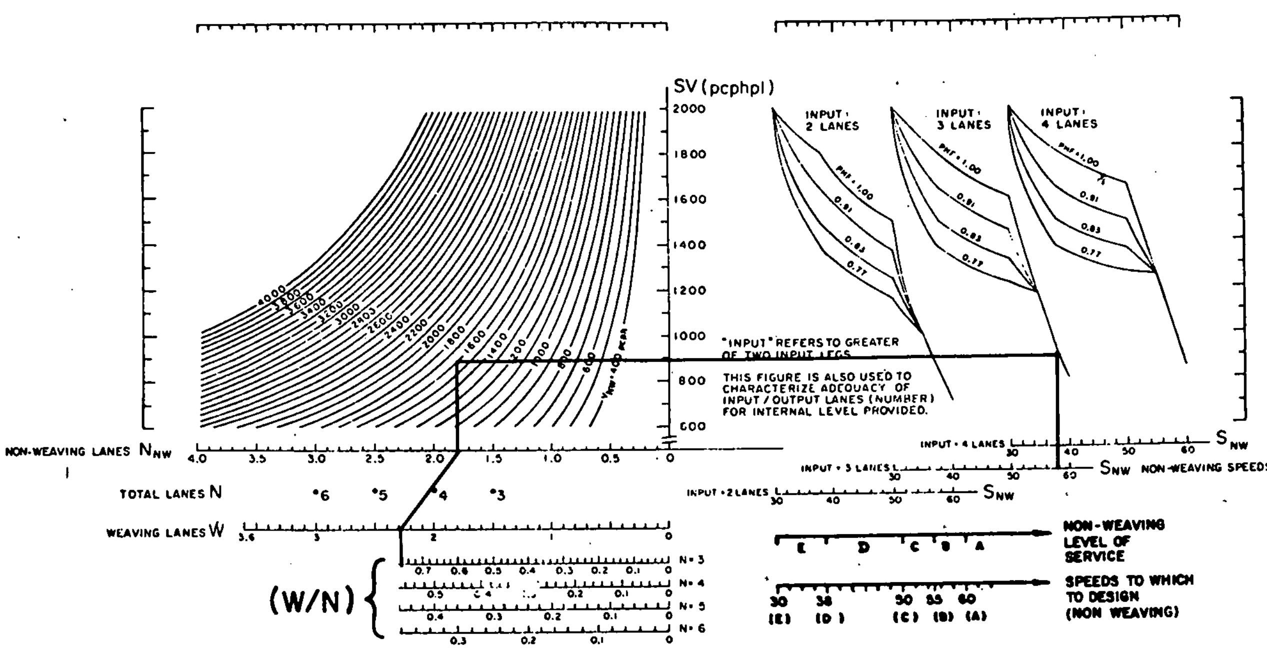


Figure E-24. Analysis of the ramp-weave problem posed in Example 3.



(A) Determine W/N by assuming $S_{nw}=50$ (solid line). Refer to W/N in (B). Determine ΔS when W is constrained and $S_{nw}=58$ (dashed line).



(B) With W constrained, determine S_{nw}. Reenter (A) with $S_{nw}=58$.

Figure E-25. Solution to the ramp-weave section analysis problem posed in Example 3.

Example 4

This problem is a variation on the analysis problem as specified and solved previously. It is, in effect, a sensitivity analysis.

Consider the problem previously specified in "Example 1," and let $N = 4$ and $L = 10$. The situation is summarized in Figure E-26.

Let R vary from 0.20 to 0.45. What lengths must exist in order to maintain the same level of operation?

As may be seen from Figure E-24 (C), h must remain unchanged in Nomograph 1 of Figure E-7 at a value of 0.133 in order to maintain the level of operation unchanged. Nomograph 2 in Figure E-8 can then be used to solve for various values of R, yielding the corresponding L. This is shown in Figure E-27 for the extreme values of R. The solution is shown graphically in Figure E-28.

The result implies that the split of weaving traffic as determined by R is an important factor in major weave operations. It is not so significant in ramp weaves—it enters in only insofar as the input/output volumes are shifted by a change in R.

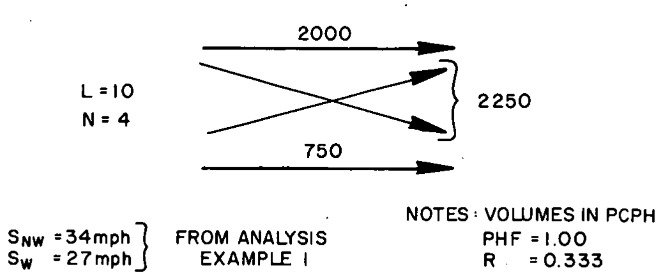


Figure E-26. Analysis of the weaving section problem posed in Example 4.

DISCUSSION OF DESIGN AND OPERATION

This section presents a number of points that are of concern to the designer and that should be considered in the context of the procedures and techniques of this appendix.

There are *differences in speed* between the two weaving flows. The speed S_w found or specified is the composite of the two. The heavier volume weaving flow is the faster of the two. This pattern is much more pronounced for ramp weaves than for major weaves.

It must be remembered that true weaving sections—both in the sense of physical weaving configuration and two significant weaving movements—are not as common as is often thought. Frequently, only one weaving flow exists and the problem is really one of merge and diverge. These are handled by the procedures of Chapter 8 of the HCM. For those true weaving sections of the ramp-weave type, it is questionable practice to make them longer than 2,000 ft. For true major weaves, the equations may be used with a caution that they are not as precise in this region.

The nomographs may be used for the longer situations by simply extending the L scale for major weaves, which is linear. An extension is shown in the nomograph of Figure E-8 (dashed).

The concept of out-of-the-realm of weaving or effective nonweaving is of recurring interest to designers. Under what conditions (length, etc.) is a weaving section indistinguishable from a normal freeway section? There are two

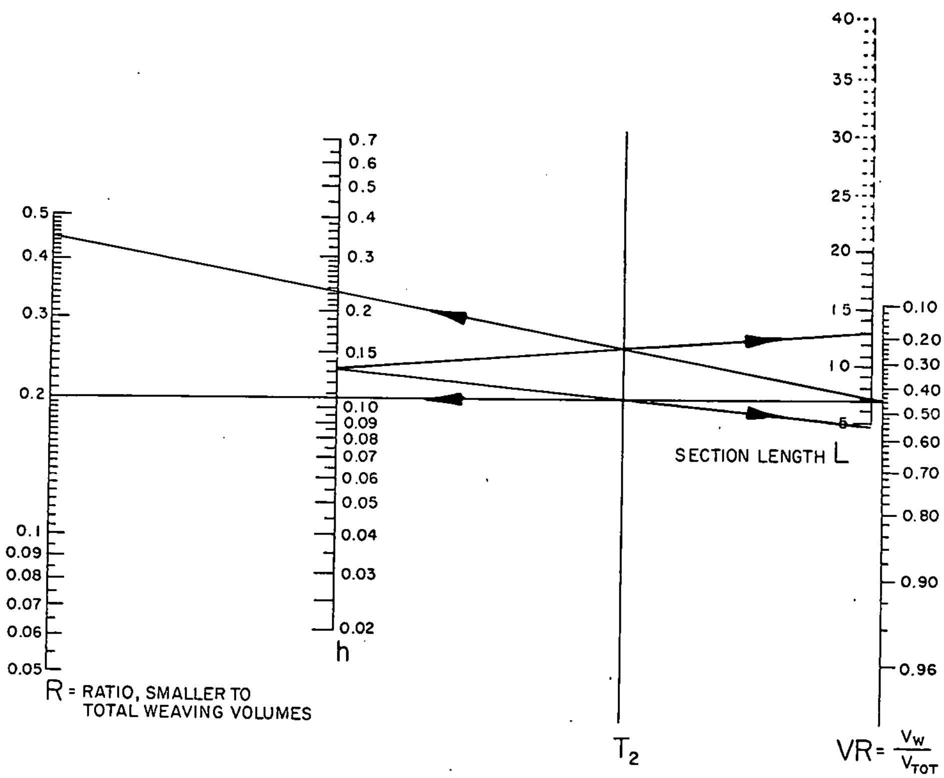


Figure E-27. Use of Nomograph 2 to solve Example 4 analysis problem.

ways of viewing the problem: (1) comparable speeds, and (2) comparable service volumes. The former can frequently be achieved, as indicated in the illustrative problems and the equations. The latter—as determined by a net service volume approaching $SV = V_{TOT}/N$—cannot be achieved in ramp weaves and cannot generally be attained in major weaves.

While one may question whether this result can be attributed to the limitations of the calibration, it must be remembered as cited earlier that (1) the merge and diverge turbulence will always exist, regardless of length, and (2) there is intensive lane changing at the beginning of the section just due to the intensive presegregation, adding to/causing the turbulence. In the case of ramp weaves, there is the added fact that there is rarely the ramp-to-ramp volume to use much of the auxiliary lane space at the activity level implied by such an SV.

It should be noted that a typical section is subjected to a *range of conditions.* Depending upon the time of day or the season, the relative flows will differ, sometimes significantly. The section may have to be designed with several flow conditions in mind. The operation under some of these may appear rather poor just because the section was designed for only one specific set of conditions.

It may also happen that the *driver population* at some times is radically different from that from which the data were collected. The composite data base generally reflects peak-period drivers at the poorer levels of service, and weekday off-peak drivers at the better levels. The impacts of recreational driving populations, to the extent that they differ from these populations, has not been ascertained. Proper advance signing and other practices can aid in avoiding pathological problems that could arise by substantial lack of the presegregation that has been observed as characteristic of weaving sections.

On the subject of shifting flow patterns, it may happen

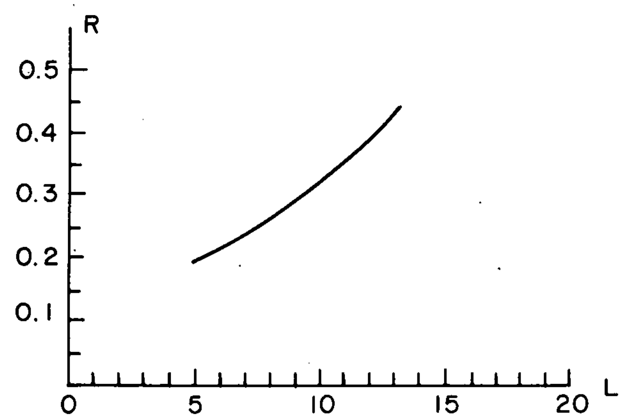


Figure E-28. Solution of Example 4 analysis problem.

that the design pattern has shifted significantly and somewhat permanently. It may be possible to *modify the section lane arrangement*—including number of lanes on each leg—with markings rather than with physical reconstruction.

It should be noted that *two-sided weaves* (sections in which one of the weaving flows is *the* largest flow and/or virtually the mainline flow) are routinely handled by the major weave classification. Two-sided weaves are just a special flow pattern, with a high VR.

Multiple weaves are more complex, and guidelines are given in a separate appendix.

A last point: the *lanes required for each nonweaving (outer) flow* can be computed separately to assure that they too are delivered. This is, as a rule, handled by checking the adequacy of the lanes on each leg. In situations where the design is marginal or the designer desires reinforcement or further insight, he may wish to compute the nonweaving lane allocation required on each side of the section.

APPENDIX F

THE COMPUTER PROGRAM FOR THE RECOMMENDED PROCEDURE

The procedure developed and recommended under this project has been implemented in FORTRAN IV for the convenience of the user. The features of the program, including input structure, are detailed in this appendix.

A copy of the program listing is included herein.

There are eight problem types that can be solved:

TYPE NUMBER	TYPE NAME
1	Ramp-weave design
2	Major weave design
3	Ramp-weave analysis
4	Major weave analysis
5	Ramp-weave analysis (continue list)
6	Major weave analysis (continue list)
7	Ramp weave, maximum V_w vs. L
8	Major weave, maximum V_w vs. L

Types 5 and 6 are simply continuations of the sort of analysis done in types 3 and 4, respectively, but without repeated headings. This allows easy comparison of a sequence of problems.

In types 7 and 8, the intent is to investigate how V_w increases as a function of length, given a level of service specification.

THE INPUT DATA

Each problem is specified on one card. This section presents some commentary on the input items. Except where specifically noted, all numeric values are entered without decimal points. Figure F-1 presents the input format.

Problem Title (A)

Eight columns are reserved for a descriptive title that is used in the output for identification.

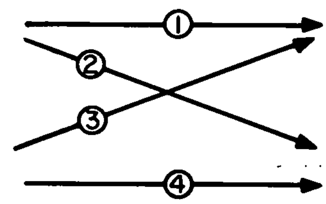
Problem Type (B)

The problem type is identified by a one-digit code as given in the enumeration above.

The problem type *must* be specified. Any problem without a proper type number is skipped with an appropriate message printed.

Volumes (C)

The four volumes must be secified in order according to the following pattern:



Any volume not specified will be taken to be zero. All volumes must be entered such that they are justified to the right-hand side of their input columns ("right-justified").

Only in types 7 and 8 are the volumes not taken exactly as they appear. In these cases, the purpose is to investigate how much V_w can be handled at various lengths L for a specified level of service. However, two "dummy" volumes *must* be specified for the weaving volumes. These must be in the same proportion as the proportion to be investigated, so that R can be fixed.

Units of Volume (D)

The units of volume are specified in one column as follows:

P   passenger cars per hour (pcph)

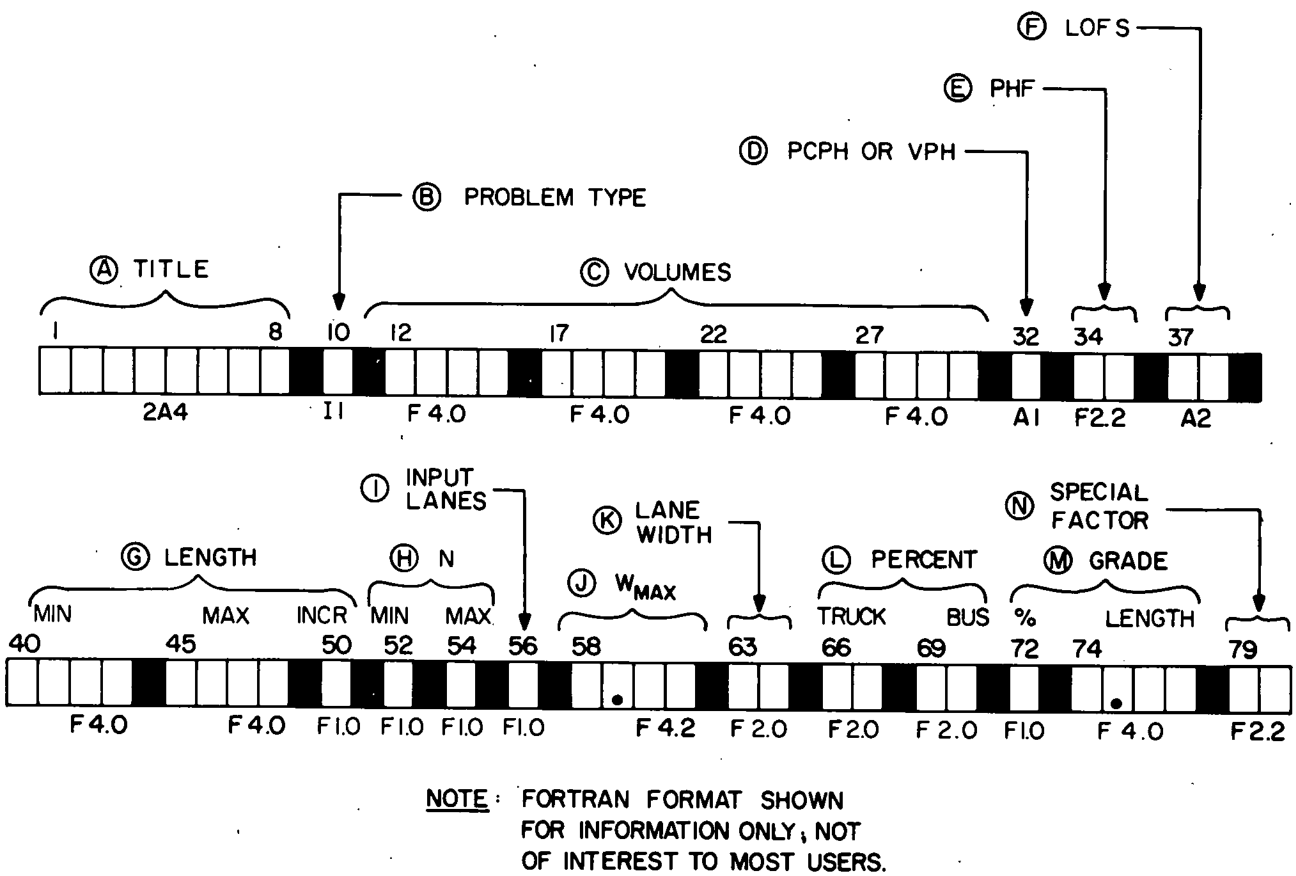


Figure F-1. Input format for weave program.

V vehicles per hour (vph)

When nothing, or any other code, is specified, pcph is assumed and an appropriate caution message is printed.

Only when "*V*" is specified does the program do *anything* with the following factors: lane width, truck percentage, bus percentage, grade, and "special" factor.

Peak-Hour Factor (E)

The peak-hour factor (PHF) is specified in two columns. For example, a PHF of 0.85 is entered as 85 in columns 34 and 35 of the input card. When nothing is specified, a PHF of 1.00 is assumed.

Level of Service (F)

The level of service (LS) is used only in design problems (types 1, 2, 7, and 8). It is ignored if an analysis problem is specified.

The level of service may be any of those used in the procedure: A, B, C, D (for ramp-weaves), D1 and D2 (for major weaves), or E. It *must* be right-justified. When none is specified, the solution steps through all levels of service.

It is recommended that level of service always be specified in types 7 and 8. The output is more orderly (for easy reading) when one problem (one card) is specified for each level; the levels are kept together.

Range of Lengths (G)

The range of lengths should be input in the following order: minimum, maximum, and increment. The increment is specified according to the following code:

1	250-ft increment
2	1,000-ft increment

The default (blank, zero, or anything else) is a 500-ft increment.

The minimum and maximum should be specified in hundreds of feet, right-justified. If the user forgets and inputs length in feet, the program will correct it.

If only one length is to be specified, it may be placed in either the "minimum" or "maximum" position, or both.

When no values are specified for "minimum" and "maximum," the program will assume 5 and 20, respectively.

The length range is used only in analysis (types 3, 4, 5, 6).

Range of Widths (H)

The width referred to is the internal width, denoted *N*, and is used in both analysis and design. If only one width is to be specified, it may be placed in either the "minimum" or "maximum" position, or both. When no values are specified for either, the program will assume 3 and 5, respectively.

For both length and width, when two non-zero values are specified, the greater of the two *must* be in the "maximum" position. If this order is violated, the problem will be solved for only the minimum value.

It is recommended that only one value of *N* be used in problem types 7 and 8, for ease in reading the numbers for one case in sequence.

Input Lanes (I)

This item refers to the greater of the number of lanes on the two input lanes. If no number is specified, it is assumed that the number is one less than the number of internal lanes, *N*. If $N = 2$, two-lane input is assumed.

Maximum W (J)

The maximum *W* is determined by configuration considerations. If no value is specified, the values of 2.30 for ramp weaves and 3.60 for major weaves hold.

Lane Width (K)

The lane width may be specified from 9 to 12 ft and must be right-justified. When no value is specified, a lane width of 12 ft is assumed.

Table 9.2 of the HCM is used for this adjustment (6-ft lateral clearance). The adjustment is made as if $N = 2$ when "Input Lanes" is specified as 2, and is made as if $N = 3$ or 4 in all other cases.

Percent Trucks and Buses (L)

Truck and bus percentages are rounded to the nearest whole percent for entry on the data card. For example, a 5-percent truck percentage is entered as 5 in column 67.

These two percentages must be right-justified. When nothing is specified, zero is assumed. The user may include buses with trucks if he wishes, but the correction factors for the two are slightly different.

Tables 9.4 and 9.5 of the HCM are used for these adjustments.

Grade (M)

The grade percentage is specified as a single digit. When nothing is specified, zero is assumed. Adjustment for grades greater than 3 percent must be made before using this program and "pcph" must be specified. Attempts to specify a higher grade will cause the problem to be skipped with an appropriate message printed.

The grade length is specified in four columns, and may be up to 4 miles. The decimal points should be included for a user's check on himself. If no length is specified, ¼ mile is assumed. If a length over 4 miles is specified, the problem is skipped.

Special Factor (N)

As the HCM indicates, correction for lateral clearance must be handled judiciously, with due engineering judgment of the regularity of the obstruction and of the driver population. Therefore, the program does not automate this.

If there is a 2-ft lateral clearance on a road with 11-ft lanes and 3 input lanes, the HCM (Table 9.2) indicates a factor of 0.93. The program would have used the factor of 0.96, acting as if there were no lateral obstruction. If the engineer judges the additional correction appropriate, he must use a "special" factor of (0.93/0.96) = 0.97. This is entered as 97 in columns 79 and 80 of the data card. The special factor is specified in two columns. When nothing is specified, a special factor of 1.00 is assumed.

DATA CHECKS

As indicated in the previous section, there are several messages that can occur in the course of processing the input data:

- "PCPH or VPH not specified. . . . PCPH assumed" (Problem continues).
- "Grade of (*over 3*) percent specified. . . . Please convert to PCPH before input" (Problem terminated).
- "Grade length of (*more than 4 mi*) specified. . . . Problem skipped" (Problem terminated).
- "Special factor (lateral clearance, etc.) of ___ is used. . . . This is not same as HCM Table 9.2 in that lane width is corrected for independently" (Problem continued).
- "Type specified as (*not 1 to 8*) . . . Problem skipped" (Problem terminated).
- "**Reminder** The user has set W maximum at ___" (Problem continues).
- "**This major weave has W max at ___. Can configuration provide it?**" (Problem continues). (This message not used for type 6.)
- "Greater of input lanes not specified. . . . One less than internal N is assumed for any value of N except $N = 2$" (Problem continues).

For all problem types except types 5 and 6, a detailed summary of the input data is printed. The two forms (one for PCPH and one for VPH) are shown in Figure F-2.

In some cases, the program uses a special subroutine to assure convergence of the iteration inherent in analysis. When this is invoked, the message "Routine HELP called. Diff of ___ mph results. Accept answer below only if diff less than 0.50. Otherwise do by hand." is printed. Even when the difference exceeds 0.50 mph, the difference (between assumed and resultant S_{nw}) rarely requires solving by hand.

OUTPUT DATA

There are three basic output headings, as shown in Figure F-3. They correspond to ramp-weave design, major weave design, and both analyses (Problem types 1 through 4). Types 5 and 6 continue under the output heading of types 3 and 4, respectively. Types 7 and 8 use the headings from types 1 and 2, respectively, with an added line specifying V_w at each step.

There are several special features in the output that deserve commentary.

```
PROBLEM TITLE:  EXP1PER1                                    PROBLEM TYPE:  RAMP WEAVE,ANALYSIS
**************                                              ************

     *****************
     ***INPUT DATA***
     *****************

            MOVEMENT:      1        2        3        4

         VOLUMES(PCPH)   1063.     313.     636.     40.     PCPH SPECIFIED...USER ASSUMED TO DO
                                                                     ALL CORRECTIONS EXCEPT PHF.
            PHF=  1.00
```

(A) PCPH SPECIFIED

```
        EXP3PER1   SPECIAL FACTOR(LATERAL CLEARANCE ETC) OF 0.92  IS USED...THIS IS
                   NOT SAME AS HCM TABLE 9.2 IN THAT LANE WIDTH IS CORRECTED
                   FOR INDEPENDENTLY

PROBLEM TITLE:  EXP3PER1                                    PROBLEM TYPE:  RAMP WEAVE,ANALYSIS
**************                                              ************

     *****************
     ***INPUT DATA***
     *****************

            MOVEMENT:      1        2        3        4            PERCENT TRUCKS:   0.
                                                                   PERCENT BUSES:    0.
         VOLUMES(VPH)    4143.     226.     437.     27.

         VOLUMES(PCPH)   4503.     246.     475.     29.           GRADE:    0. PERCENT
                                                                         0.25 MILES LONG

            PHF=  1.00                                             SPECIAL FACTOR:    0.92
```

(B) VPH SPECIFIED

Figure F-2. Two input summary forms.

Configuration Constrained?

If so, the answer "YES" is printed. In design, a message to the effect that "but S_{nw} of ___ will adjust as shown below" follows. The modification is shown on the next line. For ramp weaves, three values of ΔS are listed and solutions given.

Design Possible?

It may happen that there is just too much traffic for the level of service being considered. If so, a message to this effect will be printed in conjunction with a "NO" answer.

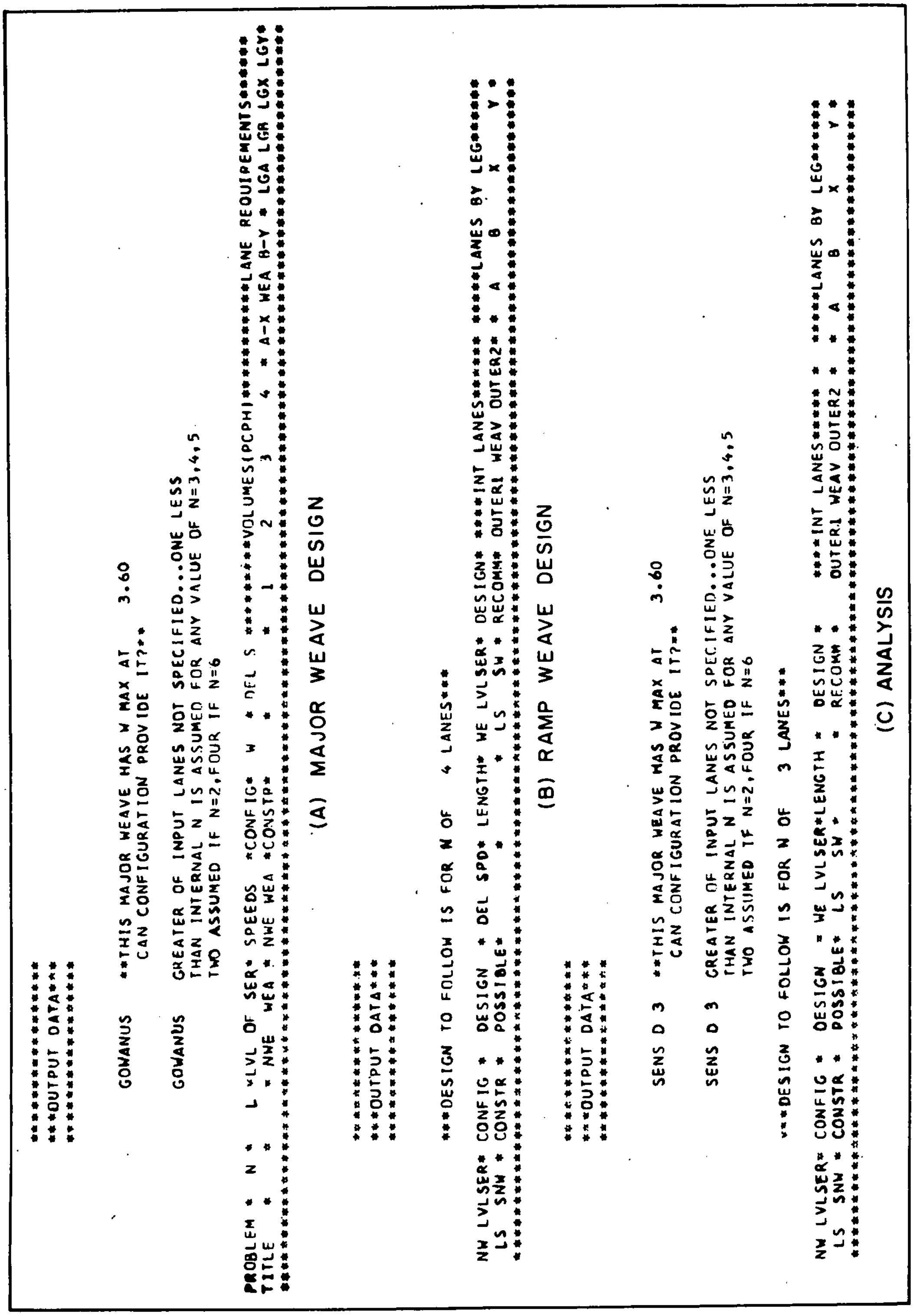


Figure F-3. The basic output headings.

Design Recommended?

If a ramp-weave design yields a length under 400 ft or over 2,500 ft, or if a major weave design yields a length under 500 ft or over 4,600 ft, the emphatic "*NO*" recommendation is printed.

If ΔS exceeds -5.0 or $+10$ mph, the simple "NO" recommendation is printed.

Level of Service F

As appropriate, messages of impossible service volumes and/or speeds are printed.

Lanes Required

For simplicity, the lanes required for each outer flow and for the weaving flow are printed in each problem. The lanes required on each leg in order to provide comparable service on the legs (comparable to the internal service volume) are also computed. If it is an analysis problem, the user may compare these to the number(s) actually available.

A NOTE ON TYPES 5 AND 6

Problem types 5 and 6 are intended to make it easier to look at a set of ramp-weave or major weave analyses (types 3 and 4). For instance, if one wishes to look at an analysis of estimated level-of-service variation by 6-min periods for 2 hr, it would be preferable not to have it spread over 20 pages with intermediate headings.

It is recommended that each set of such analyses be begun with a type 3 or 4 specification (as appropriate) so as to put the headings on the page, followed by type 5 or 6 specification for all the remaining items.

Major weave and ramp-weave analyses may be intermingled if desired, for the output format is identical.

SAMPLE PROBLEMS

Table F-1 presents the actual images of the input cards used for the sample problems of this section. Most of the problems correspond to the design and analysis examples discussed in Appendix E or to variations of them.

Problem 1

This problem was intended to be a computer version of "Design Problem 1" and is so entitled. The output is shown as Table F-2; the results do not correspond to the Appendix E findings.

Closer inspection of the output reveals that the (greater) number of input lanes is not specified so that the number is taken to be one less than the number of internal lanes. A message in the output clearly states this. Thus the number was taken as 3, rather than the 2 specified in Appendix E.

The purpose of including this discrepancy is one of emphasis: the user must take care that the problem is specified exactly as he wishes it solved.

TABLE F-1

IMAGES OF INPUT CARDS FOR SAMPLE PROBLEMS

Columns	[illegible]	Problem Type
Problem		(Col. 10)
1	DES EX 1 2 1400 400 700 800 P 91 4 2	1
2	DES EX 2 1 1680 550 800 200 V 91 4 5	1
3	DES EX 3 1 2180 550 800 200 V 91 4 5	1
4	ANA EX1 4 2000 750 1500 750 P 00 5 25 3 2	4
5	ANA EX1A 4 2000 750 1500 750 P 00 5 25 4 5 3	4
6	ANA EX 2 3 1340 830 220 70 P 91 500 3 2	3
7	ANA EX 3 3 1500 500 600 P 91 1400 3 2	3
8	HEAV VOL 3 3500 500 600 P 91 1400 3 2	3
9	EXTYPE8A 8 1000 200 300 500 P 00 1000 4 2	8

Aside from this, the problem indicates a typical solution for problem type 2 (major weave design) when the design level of service is not specified: all levels are solved for.

Observe that the (minimal) lane requirements by leg are output routinely so that the user can determine whether difficulties exist and/or how to avoid them.

Problem 2

This problem corresponds to "Design Problem 2" of Appendix E. The output is shown as Table F-3. Note that this is a configuration-constrained case, and the output is appropriate to it. One may interpolate between the points given if different ΔS or L are desired; if one sketches a curve through the three points, it should be remembered that the shape may be close to—but is not—linear.

Problem 3

This problem corresponds to "Design Problem 3" of Appendix E. The output is shown as Table F-4.

Problems 4 and 5

These two problems together correspond to "Analysis Problem 1" of Appendix E. The output is shown as Table F-5. It was handled as two problems because of the specification of (greater) number of input lanes. For $N = 3$, it is 2; and for $N = 4$ and $N = 5$, it is 3.

Note that these sample problems step over a range of lengths and/or widths. The output is a typical one for problem type 4 (major weave analysis). As was indicated in Appendix E, solutions of this type are useful in design evaluations, for the incremental improvements may be easily seen.

Problems 6, 7, and 8

These three problems are examples of problem type 3 (ramp-weave analysis). The outputs are shown in Table F-6. The first two correspond to "Analysis Example 2" and "Analysis Example 3" of Appendix E, respectively. The third has high volumes just to illustrate the output when level of service F must result.

Problem 9

This problem is an illustration of problem type 8 (major weave, maximum V_w versus L). For given outer flows, one computes—in problem types 7 and 8—the length required

TABLE F-2

SAMPLE PROBLEM 1

```
PROBLEM TITLE:  DES EX 1                                  PROBLEM TYPE:  MAJOR WEAVE,DESIGN
*************                                             ************

      ****************
      ***INPUT DATA***
      ****************

            MOVEMENT:       1        2        3        4

        VOLUMES(PCPH)   1400.     400.     700.     800.     PCPH SPECIFIED...USER ASSUMED TO DO ALL CORRECTIONS EXCEPT PHF.

            PHF= 0.91

      *****************
      ***OUTPUT DATA***
      *****************

          DES EX 1  **THIS MAJOR WEAVE HAS W MAX AT     3.60
                      CAN CONFIGURATION PROVIDE IT?**

          DES EX 1  GREATER OF INPUT LANES NOT SPECIFIED...ONE LESS
                    THAN INTERNAL N IS ASSUMED FOR ANY VALUE OF N=3,4,5
                    TWO ASSUMED IF N=2,FOUR IF N=6

      ***DESIGN TO FOLLOW IS FOR N OF   4 LANES***
```

NW LVLSER LS	SNW	CONFIG CONSTR	DESIGN POSSIBLE	WE LVLSER LS	SW	LENGTH	DESIGN RECOMM	INT LANES OUTER1	INT LANES WEAV	INT LANES OUTER2	LANES BY LEG A	LANES BY LEG B	LANES BY LEG X	LANES BY LEG Y
A	60.		NO	A	60.									
B	55.	NO	YES	B	55.	35.3	YES	1.2	2.1	0.7	1.5	1.3	1.8	1.0
C	50.	NO	YES	C	50.	16.6	YES	1.0	2.5	0.5	1.2	1.0	1.4	0.8
D1	44.	NO	YES	D1	42.	13.2	YES	0.9	2.6	0.5	1.2	1.0	1.4	0.8
D2	38.	NO	YES	D2	33.	10.0	YES	0.9	2.7	0.5	1.1	0.9	1.3	0.7
E	30.	NO	YES	E	20.	5.3	YES	0.7	2.9	0.4	0.9	0.8	1.0	0.6

TABLE F-3

SAMPLE PROBLEM 2

PROBLEM TITLE: DES EX 2

PROBLEM TYPE: RAMP WEAVE,DESIGN

INPUT DATA

MOVEMENT:	1	2	3	4
VOLUMES(VPH)	1680.	550.	800.	200.
VOLUMES(PCPH)	1764.	577.	840.	210.

PHF= 0.91

PERCENT TRUCKS: 5.
PERCENT BUSES: 0.

GRADE: 0. PERCENT
0.25 MILES LONG

SPECIAL FACTOR: 1.00

OUTPUT DATA

DESIGN TO FOLLOW IS FOR N OF 4 LANES

NW LS	LVLSER SNW	CONFIG CONSTR	DESIGN POSSIBLE	DEL SPD	LENGTH	WE LS	LVLSER SW	DESIGN RECOMM	INT LANES OUTER1	WEAV	OUTER2	LANES BY LEG A	B	X	Y
A	60.	YES	***BUT SNW OF 60. WILL ADJUST AS SHOWN BELOW												
B	55.	--		0.0	21.4	B	55.	YES	1.5	2.3	0.2	2.0	0.9	2.2	0.7
B	55.	--		5.0	13.0	C	50.	YES	1.5	2.3	0.2	2.0	0.9	2.2	0.7
B	55.	--		10.0	8.3	D	45.	YES	1.5	2.3	0.2	2.0	0.9	2.2	0.7
B	55.	YES	***BUT SNW OF 55. WILL ADJUST AS SHOWN BELOW												
B	55.	--		0.0	21.4	B	55.	YES	1.5	2.3	0.2	2.0	0.9	2.2	0.7
B	55.	--		5.0	13.0	C	50.	YES	1.5	2.3	0.2	2.0	0.9	2.2	0.7
B	55.	--		10.0	8.3	D	45.	YES	1.5	2.3	0.2	2.0	0.9	2.2	0.7
C	50.	YES	***BUT SNW OF 50. WILL ADJUST AS SHOWN BELOW												
B	55.	--		0.0	21.4	B	55.	YES	1.5	2.3	0.2	2.0	0.9	2.2	0.7
B	55.	--		5.0	13.0	C	50.	YES	1.5	2.3	0.2	2.0	0.9	2.2	0.7
B	55.	--		10.0	8.3	D	45.	YES	1.5	2.3	0.2	2.0	0.9	2.2	0.7
D	38.	YES	***BUT SNW OF 38. WILL ADJUST AS SHOWN BELOW												
B	55.	--		0.0	21.4	B	55.	YES	1.5	2.3	0.2	2.0	0.9	2.2	0.7
B	55.	--		5.0	13.0	C	50.	YES	1.5	2.3	0.2	2.0	0.9	2.2	0.7
B	55.	--		10.0	8.3	D	45.	YES	1.5	2.3	0.2	2.0	0.9	2.2	0.7
E	30.	YES	***BUT SNW OF 30. WILL ADJUST AS SHOWN BELOW												
B	55.	--		0.0	21.4	B	55.	YES	1.5	2.3	0.2	2.0	0.9	2.2	0.7
B	55.	--		5.0	13.0	C	50.	YES	1.5	2.3	0.2	2.0	0.9	2.2	0.7
B	55.	--		10.0	8.3	D	45.	YES	1.5	2.3	0.2	2.0	0.9	2.2	0.7

TABLE F-4

SAMPLE PROBLEM 3

PROBLEM TITLE: DES EX 3

PROBLEM TYPE: RAMP WEAVE,DESIGN

INPUT DATA

MOVEMENT:	1	2	3	4
VOLUMES(VPH)	2190.	550.	800.	200.
VOLUMES(PCPH)	2299.	577.	840.	210.

PHF= 0.91

PERCENT TRUCKS: 5.
PERCENT BUSES: 0.

GRADE: 0. PERCENT
0.25 MILES LONG

SPECIAL FACTOR: 1.00

OUTPUT DATA

DESIGN TO FOLLOW IS FOR N OF 4 LANES

NW LS	LVLSER SNW	CONFIG CONSTR	DESIGN POSSIBLE	DEL SPD	LENGTH	WE LS	LVLSER SW	DESIGN RECOMM	INT LANES OUTER1	WEAV	OUTER2	LANES BY LEG A	B	X	Y
A	60.	YES	***BUT SNW OF 60. WILL ADJUST AS SHOWN BELOW												
D	49.	--		0.0	16.2	D	49.	YES	1.6	2.3	0.1	2.0	0.7	2.1	0.5
D	49.	--		5.0	10.2	D	44.	YES	1.6	2.3	0.1	2.0	0.7	2.1	0.5
D	49.	--		10.0	6.6	D	39.	YES	1.6	2.3	0.1	2.0	0.7	2.1	0.5
B	55.	YES	***BUT SNW OF 55. WILL ADJUST AS SHOWN BELOW												
D	49.	--		0.0	16.2	D	49.	YES	1.6	2.3	0.1	2.0	0.7	2.1	0.5
D	49.	--		5.0	10.2	D	44.	YES	1.6	2.3	0.1	2.0	0.7	2.1	0.5
D	49.	--		10.0	6.6	D	39.	YES	1.6	2.3	0.1	2.0	0.7	2.1	0.5
C	50.	YES	***BUT SNW OF 50. WILL ADJUST AS SHOWN BELOW												
D	49.	--		0.0	16.2	D	49.	YES	1.6	2.3	0.1	2.0	0.7	2.1	0.5
D	49.	--		5.0	10.2	D	44.	YES	1.6	2.3	0.1	2.0	0.7	2.1	0.5
D	49.	--		10.0	6.6	D	39.	YES	1.6	2.3	0.1	2.0	0.7	2.1	0.5
D	38.	YES	***BUT SNW OF 38. WILL ADJUST AS SHOWN BELOW												
D	49.	--		0.0	16.2	D	49.	YES	1.6	2.3	0.1	2.0	0.7	2.1	0.5
D	49.	--		5.0	10.2	D	44.	YES	1.6	2.3	0.1	2.0	0.7	2.1	0.5
D	49.	--		10.0	6.6	D	39.	YES	1.6	2.3	0.1	2.0	0.7	2.1	0.5
E	30.	YES	***BUT SNW OF 30. WILL ADJUST AS SHOWN BELOW												
D	49.	--		0.0	16.2	D	49.	YES	1.6	2.3	0.1	2.0	0.7	2.1	0.5
D	49.	--		5.0	10.2	D	44.	YES	1.6	2.3	0.1	2.0	0.7	2.1	0.5
D	49.	--		10.0	6.6	D	39.	YES	1.6	2.3	0.1	2.0	0.7	2.1	0.5

for several V_w values at a specified level of service or set thereof.*

For problem types 7 and 8, the ratio R (= smaller to total weaving volumes) must be specified. This is done by specifying two "dummy" weaving volumes in the proper ratio.

Table F-7 gives a segment of the output for sample problem 9, and Figure F-4 shows the results. The dashed segments shown in Figure F-4 depict the artificially derived results discussed in the footnote. Clearly, these curves indicate that only the worst lengths can cause this section to perform very poorly. To look at it another way: If $V_{nw} = 1500$, $V_w = 1000$, and $N = 4$, who would want to even consider level of service E?

Note that Figure F-4 allows one to appreciate the variation of level of service with varying weaving volume and the incremental benefits of length. The representation is like HCM Figure 7.4 in appearance and function, but has a dependence on the V_{nw}, which affects shape—unlike HCM Figure 7.4.

* In some computations, the V_w, V_{nw} pair will be inconsistent with the level of service specified. For instance, $V_w = 167$ pcph, $V_{nw} = 1{,}500$ pcph, and level of service D1 when $N = 4$ must require a very short length so as to force such a terrible performance with only 1,667 pcph. These artificial combinations will make a simple plot of the output appear to bend unreasonably.

LISTING OF FORTRAN SOURCE

Table F-8 presents a listing of the FORTRAN program.

TABLE F-5

SAMPLE PROBLEMS 4 AND 5

PROBLEM TITLE: ANA EX1 — PROBLEM TYPE: MAJOR WEAVE,ANALYSIS

INPUT DATA

MOVEMENT:	1	2	3	4
VOLUMES(PCPH)	2000.	750.	1500.	750.

PCPH SPECIFIED...USER ASSUMED TO DO ALL CORRECTIONS EXCEPT PHF.

PHF= 1.00

OUTPUT DATA

ANA EX1 **THIS MAJOR WEAVE HAS W MAX AT 3.60 CAN CONFIGURATION PROVIDE IT?**

PROBLEM TITLE	N	L	LVL OF SER NWE	LVL OF SER WEA	SPEEDS NWE	SPEEDS WEA	CONFIG CONSTR	W	DEL S	VOLUMES(PCPH) 1	2	3	4	LANE REQUIREMENTS A-X	WEA	B-Y	LGA	LGB	LGX	LGY
ANA EX1	3.	5.0	E	F	30.	10.	NO	1.6	19.	2000.	750.	1500.	750.	1.0	1.6	0.4	1.4	1.1	1.8	0.8
ANA EX1	3.	10.0	E	F	30.	18.	NO	1.6	12.	2000.	750.	1500.	750.	1.0	1.6	0.4	1.4	1.1	1.8	0.8
ANA EX1	3.	15.0	E	F	32.	23.	NO	1.6	9.	2000.	750.	1500.	750.	1.0	1.6	0.4	1.4	1.2	1.8	0.8
ANA EX1	3.	20.0	E	F	34.	26.	NO	1.5	8.	2000.	750.	1500.	750.	1.1	1.5	0.4	1.5	1.2	1.9	0.8
ANA EX1	3.	25.0	E	F	35.	28.	NO	1.5	7.	2000.	750.	1500.	750.	1.1	1.5	0.4	1.5	1.2	1.9	0.8

PROBLEM TITLE: ANA EX1A — PROBLEM TYPE: MAJOR WEAVE,ANALYSIS

INPUT DATA

MOVEMENT:	1	2	3	4
VOLUMES(PCPH)	2000.	750.	1500.	750.

PCPH SPECIFIED...USER ASSUMED TO DO ALL CORRECTIONS EXCEPT PHF.

PHF= 1.00

OUTPUT DATA

ANA EX1A **THIS MAJOR WEAVE HAS W MAX AT 3.60 CAN CONFIGURATION PROVIDE IT?**

PROBLEM TITLE	N	L	LVL OF SER NWE	LVL OF SER WEA	SPEEDS NWE	SPEEDS WEA	CONFIG CONSTR	W	DEL S	VOLUMES(PCPH) 1	2	3	4	LANE REQUIREMENTS A-X	WEA	B-Y	LGA	LGB	LGX	LGY
ANA EX1A	4.	5.0	E	F	30.	18.	NO	2.6	12.	2000.	750.	1500.	750.	1.0	2.6	0.4	1.4	1.1	1.8	0.8
ANA EX1A	4.	10.0	F	E	34.	27.	NO	2.5	7.	2000.	750.	1500.	750.	1.1	2.5	0.4	1.5	1.2	1.9	0.8
ANA EX1A	4.	15.0	D2	D2	39.	34.	NO	2.5	4.	2000.	750.	1500.	750.	1.1	2.5	0.4	1.5	1.3	2.0	0.8
ANA EX1A	4.	20.0	D2	D2	42.	39.	NO	2.4	3.	2000.	750.	1500.	750.	1.2	2.4	0.4	1.6	1.3	2.0	0.9
ANA EX1A	4.	25.0	D1	D1	44.	43.	NO	2.4	2.	2000.	750.	1500.	750.	1.2	2.4	0.4	1.6	1.3	2.1	0.9
ANA EX1A	5.	5.0	E	E	32.	22.	NO	3.6	10.	2000.	750.	1500.	750.	1.0	3.6	0.4	1.4	1.2	1.8	0.8
ANA EX1A	5.	10.0	D2	D2	39.	34.	NO	3.5	4.	2000.	750.	1500.	750.	1.1	3.5	0.4	1.5	1.3	2.0	0.8
ANA EX1A	5.	15.0	D1	D1	45.	43.	NO	3.4	2.	2000.	750.	1500.	750.	1.2	3.4	0.4	1.6	1.3	2.1	0.9
ANA EX1A	5.	20.0	D1	D1	50.	50.	NO	3.3	0.	2000.	750.	1500.	750.	1.2	3.3	0.5	1.7	1.4	2.2	0.9
ANA EX1A	5.	25.0	C	C	51.	51.	NO	3.2	0.	2000.	750.	1500.	750.	1.3	3.2	0.5	1.8	1.5	2.3	1.0

TABLE F-6

SAMPLE PROBLEMS 6, 7, AND 8

```
      PROBLEM TITLE:  ANA EX 2                                     PROBLEM TYPE:  RAMP WEAVE,ANALYSIS
      *************                                                ************

           *****************
           ***INPUT DATA***
           *****************

                 MOVEMENT:      1        2        3        4

              VOLUMES(PCPH)  1340.    830.     220.      70.     PCPH SPECIFIED...USER ASSUMED TO DO ALL CORRECTIONS EXCEPT PHF.

                 PHF= 0.91

           *****************
           ***OUTPUT DATA***
           *****************

PROBLEM *  N *   L *LVL OF SER* SPEEDS  *CONFIG*  W  * DEL S *********VOLUMES(PCPH)***********LANE REQUIREMENTS******
TITLE   *    *     * NWF  WEA * NWF WEA *CONSTR*     *       *  1     2     3     4  * A-X WEA B-Y * LGA LGB LGX LGY*
*********************************************************************************************************************

ANA EX 2* 3. *  5.0*  B     D * 55. 39. *  NO  * 1.6*  16.  * 1340.  930.  220.   70.* 1.3 1.6 0.1 * 2.2 0.3 1.6 0.9*
        *    *     *        *         *      *     *       *                        *             *                *
```

```
      PROBLEM TITLE:  ANA EX 3                                     PROBLEM TYPE:  RAMP WEAVE,ANALYSIS
      *************                                                ************

           *****************
           ***INPUT DATA***
           *****************

                 MOVEMENT:      1        2        3        4

              VOLUMES(PCPH)  1500.    500.     600.       0.     PCPH SPECIFIED...USER ASSUMED TO DO ALL CORRECTIONS EXCEPT PHF.

                 PHF= 0.91

           *****************
           ***OUTPUT DATA***
           *****************

PROBLEM *  N *   L *LVL OF SER* SPEEDS  *CONFIG*  W  * DEL S *********VOLUMES(PCPH)***********LANE REQUIREMENTS******
TITLE   *    *     * NWF  WEA * NWF WEA *CONSTR*     *       *  1     2     3     4  * A-X WEA B-Y * LGA LGB LGX LGY*
*********************************************************************************************************************

ANA EX 3* 3. * 14.0*  C     D * 52. 49. *  NO  * 1.9*   3.  * 1500.  500.  600.    0.* 1.2 1.9 0.0 * 1.7 0.5 1.7 0.4*
        *    *     *        *         *      *     *       *                        *             *                *
```

```
      PROBLEM TITLE:  HEAV VOL                                     PROBLEM TYPE:  RAMP WEAVE,ANALYSIS
      *************                                                ************

           *****************
           ***INPUT DATA***
           *****************

                 MOVEMENT:      1        2        3        4

              VOLUMES(PCPH)  3500.    500.     600.       0.     PCPH SPECIFIED...USER ASSUMED TO DO ALL CORRECTIONS EXCEPT PHF.

                 PHF= 0.91

           *****************
           ***OUTPUT DATA***
           *****************

PROBLEM *  N *   L *LVL OF SER* SPEEDS  *CONFIG*  W  * DEL S *********VOLUMES(PCPH)***********LANE REQUIREMENTS******
TITLE   *    *     * NWE  WEA * NWF WEA *CONSTR*     *       *  1     2     3     4  * A-X WEA B-Y * LGA LGB LGX LGY*
*********************************************************************************************************************

                                        SV= 2146. IMPLIED BY VNW GIVEN...THIS STEP MODIFIED OR TERMINATED

                                        SV= 2424. IMPLIED BY VNW GIVEN...THIS STEP MODIFIED OR TERMINATED

HEAV VOL* 3. * 14.0*  F        LESS THAN 30.0 WITH SV=   2424. NEEDED                                              *
        *    *     *        *         *      *     *       *                        *             *                *
```

TABLE F-7

SAMPLE PROBLEM 9

PROBLEM TITLE: ' EXTYPE8A

PROBLEM TYPE: MAJOR WEAVE,MAXIMUM VW

INPUT DATA

MOVEMENT:	1	2	3	4
VOLUMES(PCPH)	1000.	200.	300.	500.

PCPH SPECIFIED...USER ASSUMED TO DO ALL CORRECTIONS EXCEPT PHF.

PHF= 1.00

OUTPUT DATA

EXTYPE8A **THIS MAJOR WEAVE HAS W MAX AT 3.60
CAN CONFIGURATION PROVIDE IT?**

NOTE THAT R= 0.40 IN THIS PROBLEM

DESIGN TO FOLLOW IS FOR N OF 4 LANES

NW LVLSER LS	SNW	CONFIG CONSTR	DESIGN POSSIBLE	WE LVLSER LS	SW	LENGTH	DESIGN RECOMM	INT LANES OUTER1	WEAV	OUTER2	LANES BY LEG A	B	X	Y
WEAVE VOLUME OF 79. PCPH YIELDS THE FOLLOWING:														
A	60.	NO	YES	A	60.	25.0	YES	1.4	1.9	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]5.	NO	YES	B	55.	17.7	YES	[illegible]	[illegible]	[illegible]	0.8	0.6	0.9	0.5
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	3.3	0.3	0.7	0.5	0.8	0.4
[illegible] PCPH YIELDS THE FOLLOWING:														
A	60.		NO	A	60.									
B	55.	NO	YES	B	55.	36.2	YES	1.0	2.5	0.5	1.5	1.2	1.7	1.0
C	50.	NO	YES	C	50.	14.0	YES	0.7	3.0	0.3	1.0	0.8	1.2	0.7
D1	44.	NO	YES	D1	42.	10.8	YES	0.6	3.1	0.3	0.9	0.8	1.1	0.6
D2	38.	NO	YES	D2	33.	7.8	YES	0.6	3.2	0.3	0.8	0.7	1.0	0.6
E	30.	NO	YES	E	20.	4.0	*NO*	0.5	3.3	0.3	0.7	0.6	0.9	0.5
WEAVE VOLUME OF 1500. PCPH YIELDS THE FOLLOWING:														
A	60.		NO	A	60.									
B	55.		NO	B	55.									
C	50.	NO	YES	C	50.	16.3	YES	0.7	3.0	0.3	1.1	0.9	1.3	0.7

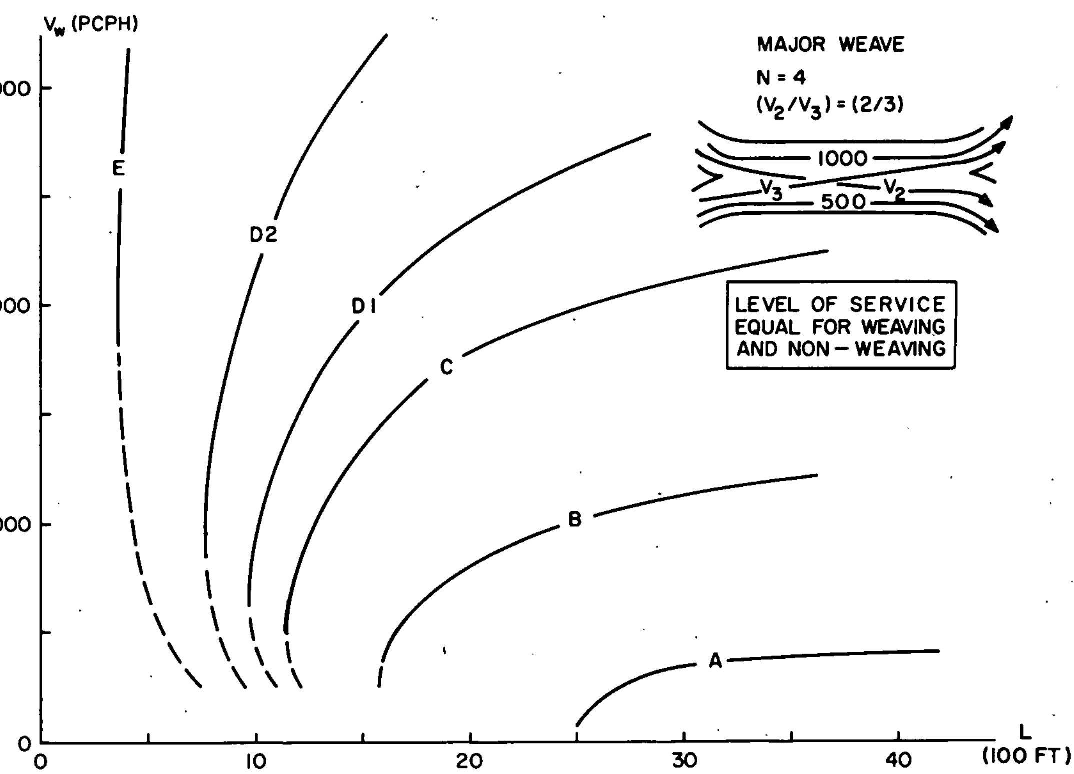


Figure F-4. Plot of results of the output for sample problem 9.

TABLE F-8

LISTING OF FORTRAN PROBLEM

```
          C      THIS PROGRAM IS RECOMMENDED WEAVING SECTION PROCEDURE
          C      DEVELOPED  UNDER NCHRP 3-15 AT THE POLYTECHNIC INSTITUTE
          C      OF NEW YORK,DEPT. OF TRANSPORTATION PLANNING AND
          C      ENGINEERING
0001              COMMON/BLKA/NINPUT,N,SVTYP,PHF,VNW,SV
0002              REAL TITLE(2),VOL(4),PCVPH,LS,LMIN,LMAX,LINCR,NMIN,NMAX,
                 *INLANE,WTOP,LANEW,TRKPER,BUSPER,GRDPER,GRDLEN,SPECFC,PORV(2),
                 *BUS,VPCPH(4),WADJUS(4,2),PHF,MAPB(3)
0003              DOUBLE PRECISION HEAD(3,6)
0004              INTEGER TYPE,MAP(16),MAPA(20),TRKFAC(8,8,3),NLOW,NHIG,LLOW,LHIG
0005              DATA HEAD/8HRAMP WEA,8HVE,DESIG,8HN       ,8HMAJOR WE,8HAVE,DESI,
                 *8HGN      ,8HRAMP WEA,8HVE,ANALY,8HSIS      ,8HMAJOR WE,8HAVE,ANAL,
                 *8HYSIS     ,8HRAMP WEA,8HVE,MAXIM,8HUM VW     ,8HMAJOR WE,8HAVE,MAXI,
                 *8HMUM VW   /
0006              DATA WADJUS/0.81,0.91,0.97,1.00,0.78,0.89,0.96,1.00/
0007              DATA BUS/1.6/
0008              DATA PORV/1HP,1HV/
0009              DATA MAP/1,2,3,4,5,5,6,6,6,6,7,7,7,7,7,7/
0010              DATA MAPA/1,1,1,2,3,4,4,5,5,6,6,6,7,7,7,7,7,8,8,8/
0011              DATA TRKFAC/64*2,5,5,4*4,3,3,5,5,4*4,3,3,7,6,4*5,4,4,7,6,4*5,4,4,
                 *7,7,6*6,7,7,6*6,4*7,4*8,4*7,4*8,10,9,8,7,6,5,4,3,10,9,8,7,6,5,4,4,
                 *10,9,8,7,6,6,5,5,10,9,8,8,7,6,5,6,10,9,9,9,8,7,7,7,10,10,9,9,4*8,
                 *12*10,4*11/
0012              DATA MAPB/2.5,10.0,5.0/
0013              REAL WMAX,WUPPER(2),VNW,VW,R,VR,W,L,WONNM,SNW,SW,NNW,XN,H,
                 * SV,SPDRW(5),SPDMW(6),LABRW(6),LABMW(7),WORDS(5),OUT(9),
                 * VLEG(4),OUTS(3),XLOUT(7),OUTMW(8),SWMW(6)
0014              INTEGER MAPC(8),NINPUT,N,SVTYP
0015              DATA SWMW/60.0,55.0,50.0,42.0,33.0,20.0/
0016              DATA SPDRW/60.0,55.0,50.0,38.0,30.0/
0017              DATA SPDMW/60.0,55.0,50.0,44.0,33.0,30.0/
0018              DATA LABRW/2H A,2H B,2H C,2H D,2H E,2H F/
0019              DATA LABMW/2H A,2H B,2H C,2HD1,2HD2,2H E,2H F/
0020              DATA WORDS/4H YES,4H NO ,4H -- , 4H*NO*,4H    /
0021              DATA MAPC/1,2,1,2,1,2,1,2/
0022              DATA WUPPER/2.3,3.6/
0023              KM=1
0024              DO 5000  KINDEX=1,1000
0025              READ(5,100,END=6000) TITLE,TYPE,VOL,PCVPH,PHF,LS,LMIN,LMAX,LINCR,
                 *NMIN,NMAX,INLANE,WTOP,LANEW,TRKPER,BUSPER,GRDPER,GRDLEN,SPECFC
0026               IF(TYPE.LE.4.OR.TYPE.GE.7) WRITE(6,10)
0027              IF(TYPE.GE.1.AND.TYPE.LE.8) GO TO 102
0028              WRITE(6,710) TITLE,TYPE
0029              GO TO 5000
0030          102 CONTINUE
0031              IF(PHF.EQ.0.0) PHF=1.00
0032              IF(PCVPH.EQ.PORV(2)) GO TO 200
0033              IF(PCVPH.NE.PORV(1)) WRITE(6,110) TITLE
0034              GO TO 500
0035          200 CONTINUE
          C   CORRECTIONS FOR VPH ARE NOW TO BE DONE
          C
          C
0036              IF(GRDPER.GE.0.0.AND.GRDPER.LE.3.0) GO TO 220
0037              WRITE(6,210) TITLE,GRDPER
0038              GO TO 5000
0039          220 IF(GRDLEN.GE.0.0.AND.GRDLEN.LE.4.0) GO TO 240
0040              WRITE(6,230) TITLE,GRDLEN
0041              GO TO 5000
0042          240 IF(GRDLEN.EQ.0.0) GRDLEN = 0.25
0043              NY = GRDLEN/0.25
0044              NY = MAP(NY)
0045              NX = GRDPER
0046              IF(NX.EQ.0) NX=1
0047              NZ = TRKPER
0048              IF(NZ.EQ.0) NZ=1
0049              IF(NZ.GT.20) NZ=20
0050              NZ = MAPA(NZ)
0051              X = TRKFAC(NZ,NY,NX)
0052              FAC = 1.00 +  TRKPER*(X-1.0)/100.0 + BUSPER*(BUS-1.0)/100.0
0053              DO 260 I=1,4
0054          260 VPCPH(I) =VOL(I)*FAC
0055              IF(SPECFC.EQ.0.0) GO TO 300
0056              WRITE(6,270) TITLE,SPECFC
0057              DO 290 I=1,4
0058          290 VPCPH(I) = VPCPH(I)/SPECFC
0059          300 NX=2
0060              IF(INLANE.EQ.2.0) NX = 1
0061              IF (SPECFC.EQ.0.0) SPECFC = 1.00
0062              NY =  LANEW - 8.0
0063              IF(NY.LE.0.OR.NY.GE.4) NY = 4
0064              LANEW = 4 + NY
0065              DO 320 I= 1,4
0066          320 VPCPH(I) = VPCPH(I)/WADJUS(NY,NX)
```

TABLE F-8 (Continued)

```
0067          IF(TYPE.EQ.5.OR.TYPE.EQ.6) GO TO 600                                 PINY0430
0068          NX= TYPE                                                             PINY0435
0069          IF(NX.EQ.7.OR.NX.EQ.8) NX=NX-2                                       PINY0440
0070          WRITE(6,340) TITLE,(HEAD(I,NX),I=1,3),(I,I=1,4),TRKPER,BUSPER,       PINY0445
             *VOL,VPCPH,GRDPER,GRDLEN,PHF,SPECFC                                   PINY0450
0071          GO TO 600                                                            PINY0455
0072      500 CONTINUE                                                             PINY0460
0073          DO 550 I=1,4                                                         PINY0465
0074      550 VPCPH(I)= VOL(I)                                                     PINY0470
0075          NX = TYPE                                                            PINY0475
0076          IF(NX.EQ.5.OR.NX.EQ.6) GO TO 600                                     PINY0480
0077          IF(NX.EQ.7.OR.NX.EQ.8) NX= NX - 2                                    PINY0485
0078          WRITE(6,570) TITLE,(HEAD(I,NX),I=1,3),(I,I=1,4),VPCPH,PHF            PINY0490
0079      600 CONTINUE                                                             PINY0495
        C  PCPH NOW ESTABLISHED AND INPUT DATA SUMMARY WRITTEN IF APPREPRIATE       PINY0500
        C     LIMITS ON N AND WILL NOW BE CHECKED                                  PINY0505
        C                                                                          PINY0510
0080          IF(NMAX.LE.NMIN) NMAX=NMIN                                           PINY0515
0081          IF(NMIN.EQ.0.0) NMIN=NMAX                                            PINY0520
0082          IF(LMAX.LE.LMIN) LMAX=LMIN                                           PINY0525
0083          IF(LMIN.EQ.0.0) LMIN=LMAX                                            PINY0530
0084          IF(LMIN.GT.99.9) LMIN=LMIN/100.0                                     PINY0535
0085          IF(LMAX.GT.99.9) LMAX =LMAX/100.0                                    PINY0540
0086          IF(LMIN.GE.2.5) GO TO 620                                            PINY0545
0087          LMIN = 5.0                                                           PINY0550
0088          LMAX = 20.0                                                          PINY0555
0089      620 IF(NMIN.GE.2.0) GO TO 640                                            PINY0560
0090          NMIN= 3.0                                                            PINY0565
0091          NMAX= 5.0                                                            PINY0570
0092      640 NLOW = NMIN                                                          PINY0575
0093          NHIG = NMAX                                                          PINY0580
0094          ND   = NHIG -NLOW                                                    PINY0585
0095          IF(ND.GE.4) NHIG = NLOW + 3                                          PINY0590
0096          IF(LINCR.NE.1.0.AND.LINCR.NE.2.0) LINCR= 3.0                         PINY0595
0097          ND= LINCR                                                            PINY0600
0098          LINCR = MAPB(ND)                                                     PINY0605
0099          LLOW = 1                                                             PINY0610
0100          LHIG = 1.0 + (LMAX-LMIN)/LINCR                                       PINY0615
        C                                                                          PINY0620
        C LIMITS ON N AND L HAVE BEEN CHECKED...MAX WIDTH NOW TO BE SET            PINY0625
        C                                                                          PINY0630
0101      700 ND = MAPC(TYPE)                                                      PINY0635
0102          WMAX = WUPPER(ND)                                                    PINY0640
0103          IF(WTOP.EQ.0.0) GO TO 730                                            PINY0645
0104          WMAX = WTOP                                                          PINY0650
0105          WRITE(6,720) WMAX                                                    PINY0655
0106      730 IF(WTOP.EQ.0.0.AND.ND.EQ.2.AND.TYPE.NE.6) WRITE(6,740) TITLE,WMAX    PINY0660
        C                                                                          PINY0665
        C     W MAX NOW SET...NOW ADDRESS NINPUT LANES                             PINY0670
        C                                                                          PINY0675
0107          NINPUT = INLANE                                                      PINY0680
0108          IF(NINPUT.NE.0) GO TO 731                                            PINY0685
0109          NFIX=MOD(TYPE,2)                                                     PINY0690
0110          IF(NFIX.EQ.1.OR.TYPE.GE.6) GO TO 731                                 PINY0695
0111          WRITE(6,750) TITLE                                                   PINY0700
0112      731 CONTINUE                                                             PINY0705
        C                                                                          PINY0710
        C     NOW THE REAL WORK BEGINS                                             PINY0715
0113          VNW = VPCPH(1)+ VPCPH(4)                                             PINY0720
0114          VW  = VPCPH(2) + VPCPH(3)                                            PINY0725
0115          VR = VW/(VW+VNW)                                                     PINY0730
0116          R=  VPCPH(2)/VW                                                      PINY0735
0117          FACTOR = R                                                           PINY0740
0118          IF(TYPE.LT.7) GO TO 733                                              PINY0745
0119          VPCPH(2)=0.0                                                         PINY0750
0120          VPCPH(3)=0.0                                                         PINY0755
0121      733 CONTINUE                                                             PINY0760
0122          IF(R.GE.0.5) R= 1.0-R                                                PINY0765
0123          IF(R.GE.0.5) R= 1.0-R                                                PINY0770
0124          VLEG(1) = VPCPH(1) + VPCPH(2)                                        PINY0775
0125          VLEG(2) = VPCPH(3) + VPCPH(4)                                        PINY0780
0126          VLEG(3) = VPCPH(1) + VPCPH(3)                                        PINY0785
0127          VLEG(4) = VPCPH(2) + VPCPH(4)                                        PINY0790
0128          SQRVR = SQRT(VR)                                                     PINY0795
0129          XLGVR = ALOG10(VR)                                                   PINY0800
0130          IF(TYPE.EQ.7.OR.TYPE.EQ.8) WRITE(6,770)R                             PINY0805
0131          GO TO (800,1500,2000,2500,3000,3500,4000,4500),TYPE                  PINY0810
0132      800 CONTINUE                                                             PINY0815
0133          NLOOP = NLOW - 1                                                     PINY0820
0134      805 NLOOP = NLOOP  + 1                                                   PINY0825
0135          N= NLOOP                                                             PINY0830
0136          XN = FLOAT(N)                                                        PINY0835
0137          IF(TYPE.EQ.1.OR.KM.EQ.1) WRITE(6,807) N                              PINY0840
0138          IF(TYPE.EQ.7) WRITE(6,4020)VW                                        PINY0845
0139          DO 806  IDUM=1,5                                                     PINY0850
```

TABLE F-8 (Continued)

```
      IF(LS.EQ.LABRW(IDUM))GO TO 808                                     PINY0855
  806 CONTINUE                                                           PINY0860
      ISTART = 0                                                         PINY0865
      IFIN = 5                                                           PINY0870
      GO TO 809                                                          PINY0875
  808 ISTART = IDUM - 1                                                  PINY0880
      IFIN   = IDUM                                                      PINY0885
  809 I= ISTART                                                          PINY0890
  810 I=I+1                                                              PINY0895
      SNW= SPORW(I)                                                      PINY0900
      OUT(1)= LABRW(I)                                                   PINY0905
      OUT(2)= SNW                                                        PINY0910
      SVTYP = 2                                                          PINY0915
      CALL SERVOL(NNW,SNW,NFLAG)                                         PINY0920
      IF(NFLAG.EQ.1) GO TO 1300                                          PINY0925
      IF(NNW.LT.XN) GO TO 900                                            PINY0930
      OUT(3) = WORDS(2)                                                  PINY0935
      OUT(4) = WORDS(2)                                                  PINY0940
      WRITE(6,850) (OUT(J),J=1,4)                                        PINY0945
      GO TO 1300                                                         PINY0950
  900 IF(W.LT.WMAX) GO TO 1000                                           PINY0955
      OUTS(1) = OUT(1)                                                   PINY0960
      OUTS(2) = OUT(2)                                                   PINY0965
      OUTS(3) = WORDS(1)                                                 PINY0970
      WRITE(6,910) OUTS,OUTS(2)                                          PINY0975
      W = WMAX                                                           PINY0980
      NNW=XN-W                                                           PINY0985
      SVTYP = 1                                                          PINY0990
      CALL SERVOL(NNW,SNW,NFLAG)                                         PINY0995
      IF(NFLAG.EQ.1) GO TO 1300                                          PINY1000
      XLGSNW = ALOG10(SNW)                                               PINY1005
      DO 975 K= 5,15,5                                                   PINY1010
      DELS =    FLOAT(K) - 5.0                                           PINY1015
      L=(DELS+109.5-50.7*XLGSNW)/104.8                                   PINY1020
      L=((1.0/L)**2)-3.0                                                 PINY1025
      SW = SNW - DELS                                                    PINY1030
      DO 940  KA = 1,5                                                   PINY1035
      IF(SW.GE.SPORW(KA)) GO TO 945                                      PINY1040
  940 CONTINUE                                                           PINY1045
      KA = 6                                                             PINY1050
  945 OUT(7) = LABRW(KA)                                                 PINY1055
      OUT(2) = SNW                                                       PINY1060
      DO 950 KA = 1,5                                                    PINY1065
      IF(SNW.GE.SPORW(KA)) GO TO 955                                     PINY1070
  950 CONTINUE                                                           PINY1075
      KA = 6                                                             PINY1080
  955 OUT(1) = LABRW (KA)                                                PINY1085
      OUT(4) = WORDS(3)                                                  PINY1090
      OUT(6)=L                                                           PINY1095
      OUT(5) = DELS                                                      PINY1100
      OUT(8) = SW                                                        PINY1105
      OUT(9) = WORDS(1)                                                  PINY1110
      IF(L.LT.4.0.OR.L.GT.25.0) OUT(9) = WORDS(4)                        PINY1115
      CALL  LANOUT(XLOUT,VPCPH,W,VLEG,SV)                                PINY1120
      WRITE(6,970) OUT(1),OUT(2),(OUT(J),J=4,9),XLOUT                    PINY1125
  975 CONTINUE                                                           PINY1130
      GO TO 1300                                                         PINY1135
 1000 XLGWN = ALOG10(W/XN)                                               PINY1140
      DELS = (XLGWN + 0.615 +0.606*SQRVR)/(-0.003365)                    PINY1145
      XLGSNW = ALOG10(SNW)                                               PINY1150
      L=((104.8/(DELS+109.5-50.7*XLGSNW))**2)-3.0                        PINY1155
      OUT(3) = WORDS(2)                                                  PINY1160
      OUT(4) = WORDS(3)                                                  PINY1165
      OUT(6) = L                                                         PINY1170
      OUT(5) = DELS                                                      PINY1175
      SW = SNW - DELS                                                    PINY1180
      DO 1010 KA=1,5                                                     PINY1185
      IF(SW.GE.SPORW(KA)) GO TO 1020                                     PINY1190
 1010 CONTINUE                                                           PINY1195
      KA = 6                                                             PINY1200
 1020 OUT(7) = LABRW(KA)                                                 PINY1205
      OUT(8)=SW                                                          PINY1210
      OUT(9)=WORDS(1)                                                    PINY1215
      IF(DELS.LT.(-5.0).OR.DELS.GT.10.0) OUT(9)=WORDS(2)                 PINY1220
      IF(L.LT.4.0.OR.L.GT.25.0)  OUT(9)=WORDS(4)                         PINY1225
      CALL LANOUT(XLOUT,VPCPH,W,VLEG,SV)                                 PINY1230
      WRITE(6,1050) OUT,XLOUT                                            PINY1235
 1300 CONTINUE                                                           PINY1240
      IF(I.LT.IFIN) GO TO 810                                            PINY1245
      IF(NLOOP.LT.NHIG) GO TO 805                                        PINY1250
      IF(TYPE.EQ.7) GO TO 4050                                           PINY1255
      GO TO 5000                                                         PINY1260
 1500 CONTINUE                                                           PINY1265
      NLOOP=NLOW-1                                                       PINY1270
```

TABLE F-8 (Continued)

```
 1505 NLOOP=NLOOP+1
      N=NLOOP
      XN=FLOAT(N)
      IF(TYPE.EQ.2.OR.KM.EQ.1) WRITE(6,1507) N
      IF(TYPE.EQ.8) WRITE(6,4520)VW
      DO 1506 IDUM=1,6
      IF(LS.EQ.LABMW(IDUM)) GO TO 1508
 1506 CONTINUE
      ISTART=0
      IFIN=6
      GO TO 1509
 1508 ISTART=IDUM-1
      IFIN=IDUM
 1509 I=ISTART
 1510 I=I+1
      SNW=SPOMW(I)
      SVTYP=2
      CALL SERVOL(NNW,SNW,NFLAG)
      IF(NFLAG.EQ.1) GO TO 1950
      OUTMW(1)=LABMW(I)
      OUTMW(2)=SNW
      OUTMW(5)=LABMW(I)
      OUTMW(6)=SWMW(I)
      IF(NNW.LT.XN) GO TO 1540
      WRITE(6,1520) OUTMW(1),OUTMW(2)
      GO TO 1950
 1540 CONTINUE
      W=XN-NNW
      XLGSW=ALOG10(SWMW(I))
      XLGWN=ALOG10(W/XN)
      H=XLGWN+1.16-0.660*VR-0.372*XLGSW
      IF(W.LT.WMAX) GO TO 1595
      OUTMW(3)=WORDS(1)
      WRITE(6,1560) (OUTMW(J),J=1,3)
      W=WMAX
      NNW=XN-W
      SVTYP=1
      CALL SERVOL(NNW,SNW,NFLAG)
      IF(NFLAG.EQ.1) GO TO 1950
      XLGSW=ALOG10(SWMW(I))
      XLGWN=ALOG10(W/XN)
      H=XLGWN+1.16-0.660*VR-0.372*XLGSW
      DO 1570 KA=1,6
      IF(SNW.GE.SPOMW(KA)) GO TO 1575
 1570 CONTINUE
      KA=7
 1575 OUTMW(1)=LABMW(KA)
      OUTMW(2)=SNW
      IF(H.GT.0.0) GO TO 1600
 1591 OUTMW(4)=WORDS(2)
      WRITE(6,1590) OUTMW(1),OUTMW(2),(OUTMW(J),J=4,6)
      GO TO 1950
 1595 OUTMW(3)=WORDS(2)
      IF(H.LE.0.0) GO TO 1591
 1600 OUTMW(4)=WORDS(1)
      L=H/(-3.10*R*XLGVR)
      L=ALOG(L)/(-0.1)
      IF(L.LE.0.0) GO TO 1591
      OUTMW(7)=L
      OUTMW(8)=WORDS(1)
      DELS=OUTMW(2)-OUTMW(6)
      IF(DELS.LT.(-5.0).OR.DELS.GT.10.0) OUTMW(8)=WORDS(2)
      IF(L.LT.5.0.OR.L.GT.46.0) OUTMW(8)=WORDS(4)
      CALL LANCUT(XLOUT,VPCPH,W,VLEG,SV)
      IF(OUTMW(3).EQ.WORDS(1)) OUTMW(3)=WORDS(5)
      WRITE(6,1620) OUTMW,XLOUT
 1950 CONTINUE
      IF(I.LT.IFIN) GO TO 1510
      IF(NLOOP.LT.NHIG) GO TO 1505
      IF(TYPE.EQ.8) GO TO 4550
      GO TO 5000
C
C     THE BASIC DESIGN FEATURES ARE NOW COMPLETED...ANALYSIS FOLLOWS
C
 2000 CONTINUE
      IF(TYPE.EQ.3) WRITE(6,2010)
      DO 2450 NLOOP=NLOW,NHIG
      DO 2450 NLEN=LLOW,LHIG
      N=NLOOP
      XN=N
      L=LMIN+LINCR*(NLEN-1)
      SNWIN=60.0
 2050 DELS=-109.5+104.8/SQRT(L+3.0)+50.7*ALOG10(SNWIN)
      W=XN*10.0**(-0.615+0.606*SQRVR-0.00365*DELS)
```

TABLE F-8 (Continued)

```
            IF(W.GE.WMAX) W=WMAX
            NNW=XN-W
            SVTYP=1
            CALL SERVOL(NNW,SNW,NFLAG)
            IF(NFLAG.EQ.0) GO TO 2100
            IF(SNWIN.EQ.30.0) GO TO 2080
            SNWIN=30.0
            GO TO 2050
       2080 WRITE(6,2090) TITLE,XN,L,LABRW(6),SNWIN,SV
            GO TO 2450
       2100 SNWOUT=SNW
            DIFF=SNWIN-SNWOUT
            IF(DIFF.LT.0.50.AND.DIFF.GT.(-0.50)) GO TO 2200
            SNWIN=SNWIN-0.70*DIFF
            IF(SNWIN.GT.60.0) GO TO 2080
            IF(SNWIN.LT.30.0) SNWIN=30.0
            GO TO 2050
       2200 SW=SNW-DELS
            CALL LANOUT(XLOUT,VPCPH,W,VLEG,SV)
            DO 2220 KA=1,5
            IF(SNW.GE.SPDRW(KA)) GO TO 2225
       2220 CONTINUE
            KA=6
       2225 OUT(1)=LABRW(KA)
            DO 2240 KA=1,5
            IF(SW.GE.SPDRW(KA)) GO TO 2245
       2240 CONTINUE
            KA=6
       2245 OUT(2)=LABRW(KA)
            OUT(3) = WORDS(2)
            IF(W.GE.WMAX) OUT(3)=WORDS(1)
            CALL LANOUT(XLOUT,VPCPH,W,VLEG,SV)
            WRITE(6,2300) TITLE,XN,L,OUT(1),OUT(2),SNW,SW,OUT(3),W,DELS,
           *VPCPH,XLOUT
       2450 CONTINUE
            GO TO 5000
       2500 CONTINUE
            IF(TYPE.EQ.4) WRITE(6,2010)
            DO 2950 NLOOP=NLOW,NHIG
            DO 2950 NLEN=LLOW,LHIG
            NSAVE =0
            EP=0.7
            N=NLOOP
            XN=NLOOP
            L=LMIN+LINCP*(NLEN-1)
            H=-3.10*R*XLGVR*EXP(-0.1*L)
            CONST=-1.16+0.650*VR+H
            SNWIN=60.0
       2550 SVTYP=2
            NSAVE=NSAVE+1
            IF(NSAVE.GT.100) GO TO 2952
            SNW=SNWIN
            CALL SERVOL(NNW,SNW,NFLAG)
            IF(NNW.LT.XN) GO TO 2600
            IF(SNWIN.GT.30.0) GO TO 2560
            WRITE(6,2555) TITLE,XN,L,VPCPH
            GO TO 2950
       2560 SNWIN=SNWIN-5.0
            IF(SNWIN.LT.30.0) SNWIN=30.0
            GO TO 2550
       2600 W=XN-NNW
            IF(W.GE.WMAX) W=WMAX
            NNW=XN-W
            IF(W.LT.WMAX) GO TO 2620
            SVTYP=1
            CALL SERVOL(NNW,SNW,NFLAG)
            SNWIN=SNW
       2620 XLGWN=ALOG10(W/XN)
            SW=10.0**((XLGWN-CONST)/0.372)
            DELS=48.3-27.4*ALOG10(SW)-0.146*(12.5)
            IF(DELS.LT.0.0) DELS=0.0
            SNWOUT=SW+DELS
            IF(W.LT.WMAX) GO TO 2700
            IF(SNWOUT.GE.60.0) SNWOUT=60.0
            IF(SNWOUT.LE.SNWIN) GO TO 2800
            SNWIN=SNWIN+ EP*(SNWOUT-SNWIN)
            IF(NSAVE.GT.10) EP=0.4
            IF(NSAVE.GT.20) EP=0.3
            GO TO 2550
       2700 DIFF=SNWIN-SNWOUT
            IF(DIFF.LT.0.50.AND.DIFF.GT.(-0.50)) GO TO 2800
            IF(SW.GE.20.0) GO TO 2720
            IF(SNWIN.EQ.30.0) GO TO 2800
            SNWIN=30.0
            GO TO 2550
       2720 SNWIN=SNWIN+ EP*(SNWOUT-SNWIN)
            IF(NSAVE.GT.10) EP=0.4
```

TABLE F-8 (Continued)

```
      IF(NSAVE.GT.20) EP=0.3                                            PINY2130
      GO TO 2550                                                        PINY2135
 2900 OUT(3)=WORDS(2)                                                   PINY2140
      IF(W.GE.WMAX) OUT(3)=WORDS(1)                                     PINY2145
      SNW=SNWIN                                                         PINY2150
      DO 2820 KA=1,6                                                    PINY2155
      IF(SNW.GE.SPDMW(KA)) GO TO 2825                                   PINY2160
 2820 CONTINUE                                                          PINY2165
      KA=7                                                              PINY2170
 2825 OUT(1)=LABMW(KA)                                                  PINY2175
      DO 2840 KA=1,6                                                    PINY2180
      IF(SW.GE.SWMW(KA)) GO TO 2845                                     PINY2185
 2840 CONTINUE                                                          PINY2190
      KA=7                                                              PINY2195
 2845 OUT(2)=LABMW(KA)                                                  PINY2200
      CALL LANOUT(XLOUT,VPCPH,W,VLEG,SV)                                PINY2205
      WRITE(6,2300) TITLE,XN,L,OUT(1),OUT(2),SNW,SW,OUT(3),W,DELS,      PINY2210
     *VPCPH,XLOUT                                                       PINY2215
      GO TO 2950                                                        PINY2220
 2952 CALL HELP(WMAX,CONST,SNW,SW,DIFW)                                 PINY2225
      SNWIN=SNW                                                         PINY2230
      WRITE(6,2953)TITLE,DIFW                                           PINY2235
 2950 CONTINUE                                                          PINY2240
      GO TO 5000                                                        PINY2245
C                                                                       PINY2250
C     ALL BASICS FOR DESIGN/ANALYSIS NOW WRITTEN                        PINY2255
C                                                                       PINY2260
 3000 CONTINUE                                                          PINY2265
      GO TO 2000                                                        PINY2270
 3500 CONTINUE                                                          PINY2275
      GO TO 2500                                                        PINY2280
 4000 CONTINUE                                                          PINY2285
      KM=0                                                              PINY2290
 4010 KM=KM+1                                                           PINY2295
 4015 VR=0.05*FLOAT(KM)                                                 PINY2300
      SQRVR=SQRT(VR)                                                    PINY2305
      XLGVR=ALOG10(VR)                                                  PINY2310
      VW=VNW*VR/(1.0-VR)                                                PINY2315
      VPCPH(2)=FACTOR*VW                                                PINY2320
      VPCPH(3)=VW-VPCPH(2)                                              PINY2325
      VLEG(1)=VPCPH(1)+VPCPH(2)                                         PINY2330
      VLEG(2)=VPCPH(3)+VPCPH(4)                                         PINY2335
      VLEG(3)=VPCPH(1)+VPCPH(3)                                         PINY2340
      VLEG(4)=VPCPH(2)+VPCPH(4)                                         PINY2345
      IF(TYPE.EQ.3) GO TO 4516                                          PINY2350
      GO TO 900                                                         PINY2355
 4050 CONTINUE                                                          PINY2360
      IF(KM.LT.15) GO TO 4010                                           PINY2365
      GO TO 5000                                                        PINY2370
 4500 CONTINUE                                                          PINY2375
      KM=0                                                              PINY2380
 4510 KM=KM+1                                                           PINY2385
      VR=0.05*FLOAT(KM)+0.15                                            PINY2390
      GO TO 4015                                                        PINY2395
 4516 CONTINUE                                                          PINY2400
      GO TO 1500                                                        PINY2405
 4550 CONTINUE                                                          PINY2410
      IF(KM.LT.14) GO TO 4510                                           PINY2415
      GO TO 5000                                                        PINY2420
 5000 CONTINUE                                                          PINY2425
 6000 WRITE(6,6100)                                                     PINY2430
   10 FORMAT(1H1//)                                                     PINY2435
  100 FORMAT(2A4,1X,I1,4(1X,F4.0),1X,A1,1X,F2.2,1X,A2,2(1X,F4.0),       PINY2440
     *4(1X,F1.0),1X,F4.2,3(1X,F2.0),1X,F1.0,1X,F4.2,1X,F2.2)            PINY2445
  110 FORMAT(20X,2A4,2X,42HPCPH OR VPH NOT SPECIFIED...PCPH SPECIFIED//)PINY2450
  210 FORMAT(20X,2A4,2X,8HGRADE OF,F5.0,57H  PERCENT SPECIFIED...PLEASE PINY2455
     *CONVERT TO PCPH BEFORE INPUT//)                                   PINY2460
  230 FORMAT(20X,2A4,2X,15HGRADE LENGTH OF,F5.2,29H  SPECIFIED...PROBLEMPINY2465
     * SKIPPED//)                                                       PINY2470
  270 FORMAT(20X,2A4,2X,40HSPECIAL FACTOR(LATERAL CLEARANCE ETC) OF,    PINY2475
     *F5.2,19H  IS USED...THIS IS/30X,57HNOT SAME AS HCM TABLE 9.2 IN THPINY2480
     *AT LANE WIDTH IS CORRECTED/30X,17HFOR INDEPENDENTLY//)            PINY2485
  340 FORMAT(10X,14HPROBLEM TITLE:,2X,2A4,36X,13HPROBLEM TYPE:,2X,3A8/10PINY2490
     *X,13                                                              PINY2495
     *(1H*),47X,12(1H*)//15X,16(1H*)/15X,16H***INPUT DATA***/15X,16(1H*)PINY2500
     *//25X,9HMOVEMENT:,I6,3I8,11X,15HPERCENT TRUCKS:,F4.0/75X,14HPERCENPINY2505
     *T BUSES:,   F5.0/21X,12HVOLUMES(VPH),4F8.0//21X,13HVOLUMES(PCPH), PINY2510
     *F7.0,3F8.0,10X, 6HGRADE:,F5.0,8H PERCENT/81X,F5.2,11H MILES LONG//PINY2515
     * 25X,4HPHF=,F5.2,41X,15HSPECIAL FACTOR:,F8.2//15X,17(1H*)/15X,17H*PINY2520
     ***OUTPUT DATA***/15X,17(1H*)///)                                  PINY2525
  570 FORMAT(10X,14HPROBLEM TITLE:,2X,2A4,36X,13HPROBLEM TYPE:,2X,3A8/10PINY2530
     *X,13                                                              PINY2535
     *(1H*),47X,12(1H*)//15X,16(1H*)/15X,16H***INPUT DATA***/15X,16(1H*)PINY2540
     *//25X,9HMOVEMENT:,   I6,3I8//21X,13HVOLUMES(PCPH),F7.0,3F8.0,5X,  PINY2545
     *63HPCPH SPECIFIED...USER ASSUMED TO DO ALL CORRECTIONS EXCEPT PHF.PINY2550
     *//25X,4HPHF=,F5.2//15X,17(1H*)/15X,17H***OUTPUT DATA***/15X,17(1H*PINY2555
     *)///)                                                             PINY2560
  710 FORMAT(20X,2A4,2X,17HTYPE SPECIFIED AS,I5,17H  PROBLEM SKIPPED/)  PINY2565
```

TABLE F-8 (Continued)

```
0457          720 FORMAT(20X,43H***REMINDER***THE USER HAS SET W MAXIMUM AT,F8.2/)  PINY2570
0458          740 FORMAT(20X,2A4,2X,31H**THIS MAJOR WEAVE HAS W MAX AT,F8.2/32X,31HCPINY2575
                 *AN CONFIGURATION PROVIDE IT?**/)                                   PINY2580
0459          750 FORMAT(20X,2A4,2X,47HGREATER OF INPUT LANES NOT SPECIFIED...ONE LEPINY2585
                 *SS/30X,51HTHAN INTERNAL N IS ASSUMED FOR ANY VALUE OF N=3,4,5/30X,PINY2590
                 *30HTWO ASSUMED IF N=2,FOUR IF N=6/)                                PINY2595
0460          770 FORMAT(40X,12HNOTE THAT R=,F6.2,16H IN THIS PROBLEM/)              PINY2600
0461          807 FORMAT(15X,31H***DESIGN TO FOLLOW IS FOR N OF,I4,9H LANES***//4X, PINY2605
                 *58HNW LVLSER* CONFIG *  DESIGN  * DEL SPD* LENGTH* WE LVLSER*,     PINY2610
                 *52H DESIGN* ****INT LANES****** *****LANES BY LEG******/5X,        PINY2615
                 *57HLS  SNW * CONSTR *  POSSIBLE*        *       * LS   SW *,       PINY2620
                 *52H RECOMM* OUTER1 WEAV OUTER2* *  A     B      X      Y */4X,110(1H*PINY2625
                 *))                                                                 PINY2630
0462          850 FORMAT(5X,A2,F5.0,4H *   ,A4,3H  *,3X,A4,1X,40H***TOO MUCH VNW...CAPINY2635
                 *NNOT EVEN HANDLE VNW  / 13X,1H*,9X,1H*,10X,1H*,10X,1H*,7X,1H*,9X, PINY2640
                 *1H*,23X,1H*,24X,1H*)                                               PINY2645
0463          910 FORMAT(5X,A2,F5.0,4H *   ,A4,2X,13H***BUT SNW OF,F5.0,27H WILL ADJUPINY2650
                 *ST AS SHOWN BELOW/13X,1H*,8X,1H*,10X,1H*,8X,1H*,7X,1H*,10X,1H*,   PINY2655
                 *7X,1H*,19X,1H*,1X,1H*,21X,1H*)                                     PINY2660
0464          970 FORMAT(6X,A2,F5.0,1H*, 2X,A4,2X,1H*,8X,2X,1H*,1X,F5.1,2X,1H*,      PINY2665
                 *2X,F4.1,2H *,2X,A2,F5.0,2H *,2X,A4,2H *,     3F6.1,2H *,2H *,F3.1,PINY2670
                 *F5.1,2F6.1,2H */13X,1H*,8X,1H*,10X,1H*,8X,1H*,7X,1H*,       10X,1H*PINY2675
                 *,7X,1H*,19X,3H* *,21X,1H*)                                         PINY2680
0465         1050 FORMAT(5X,A2,F5.0,2H *,2X,A4,2X,1H*,4X,A4,2X,1H*,1X,F5.1,2X,1H*,  PINY2685
                 *2X,F4.1,2H *,2X,A2,F5.0,2H *,2X,A4,2H *,     3F6.1,2H *,2H *,F3.1,PINY2690
                 *F5.1,2F6.1,2H */13X,1H*,8X,1H*,10X,1H*,8X,2H*,7X,1H*,       10X,1H*PINY2695
                 *,7X,1H*,19X,3H* *,21X,1H*)                                         PINY2700
0466         1507 FORMAT(15X,31H***DESIGN TO FOLLOW IS FOR N OF,I4,9H LANES***//4X, PINY2705
                 *10HNW LVLSER*,1X,8HCONFIG *,2X, 9HDESIGN  *,1X,18HWE LVLSER*LENGTHPINY2710
                 * *,2X,8HDESIGN *,4X,20H****INT LANES***** *,2X,23H*****LANES BY LEPINY2715
                 *G******/4X,10H LS  SNW *,1X,8HCONSTR *,2X,9HPOSSIBLE*,1X,18H LS   PINY2720
                 *SW *        *,2X,8HRECOMM *,4X,20HOUTER1 WEAV OUTER2 *,2X,23H*  A  PINY2725
                 *  B     X       Y */4X,108(1H*)//)                                  PINY2730
0467         1520 FORMAT(5X,A2,F5.0,4H *   ,A4,3H  *,3X,A4,1X,40H***TOO MUCH VNW...CAPINY2735
                 *NNOT EVEN HANDLE VNW  / 13X,1H*,8X,1H*,10X,1H*,18X,1H*,7X,1H*,9X, PINY2740
                 *1H*,23X,1H*,24X,1H*)                                               PINY2745
0468         1560 FORMAT(5X,A2,F5.0,2H *,2X,A4,2X,37H***BUT SNW WILL ADJUST AS SHOWNPINY2750
                 * BELOW/13X,1H*,8X,1H*,10X,1H*,10X,1H*,7X,1H*,9X,1H*,23X,1H*,24X,1HPINY2755
                 **)                                                                 PINY2760
0469         1590 FORMAT(5X,A2,F5.0,2H *,8X,1H*,3X,A4,3X,1H*,2X,A2,F4.0,2X,1H*,7X,1HPINY2765
                 **,9X,1H*,23X,1H*,24X,1H*/13X,1H*,8X,1H*,10X,1H*,10X,1H*,7X,1H*,9X,PINY2770
                 *1H*,23X,1H*,24X,1H*)                                               PINY2775
0470         1620 FORMAT(5X,A2,F5.0,2H *,2X,A4,2X,1H*,3X,A4,3X,1H*,2X,A2,F4.0,2X,1H*PINY2780
                 *,F6.1,2H *,3X,A4,2X,1H*,5X,F4.1,2F6.1,2X,1H*,2X,1H*,F4.1,F5.1,2F6.PINY2785
                 *1,1H*/13X,1H*,8X,1H*,10X,1H*,10X,1H*,7X,1H*,9X,1H*,23X,1H*,24X,1H*PINY2790
                 *)                                                                  PINY2795
0471         2010 FORMAT(1X,48HPROBLEM *  N *    L *LVL OF SER* SPEEDS  *CONFIG*,    PINY2800
                 *39H  W   * DEL S *********VOLUMES(PCPH)****, 7(1H*),17HLANE REQUIREPINY2805
                 *MENTS, 6(1H*)/1X,  41HTITLE    *      *       * NWF  WEA * NWE WEA *, PINY2810
                 *60HCONSTR*       *         *   1     2      3      4   * A-X WEA B-Y *, PINY2815
                 *17H LGA LGB LGX LGY*/1X,118(1H*)//)                                PINY2820
0472         2090 FORMAT(1X,2A4,1H*,F3.0,2H *,F5.1,1H*,1X,A2,9X, 9HLESS THAN,F5.1,  PINY2825
                 * 9H WITH SV=,F8.0, 7H NEEDED   ,47X,1H*/9X,1H*,                    PINY2830
                 *4X,1H*,5X,1H*,10X,1H*,9X,1H*,7X,1H*,4X,1H*,7X,1H*,24X,1H*,13X,1H*,PINY2835
                 *16X,1H*)                                                           PINY2840
0473         2300 FORMAT(1X,2A4,1H*,F3.0,2H *,F5.1,1H*,1X,A2,4X,A2,2H *,2F4.0,3H * ,PINY2845
                 *A4,2X,1H*,F4.1,1H*,F5.0,2X,1H*,4F6.0,1H*,3F4.1,2H *,4F4.1,1H*/9X, PINY2850
                 *1H*,                                                               PINY2855
                 *4X,1H*,5X,1H*,10X,1H*,9X,1H*,7X,1H*,4X,1H*,7X,1H*,24X,1H*,13X,1H*,PINY2860
                 *16X,1H*)                                                           PINY2865
0474         2555 FORMAT(1X,2A4,1H*,F3.0,2H *,F5.1,1H*,2X,31HNOT ENOUGH N TO HANDLE PINY2870
                 *EVEN VNW,8X,1H*,4F6.0,1H*,13X,1H*,16X,1H*/9X,1H*,                  PINY2875
                 *4X,1H*,5X,1H*,10X,1H*,9X,1H*,7X,1H*,4X,1H*,7X,1H*,24X,1H*,13X,1H*,PINY2880
                 *16X,1H*)                                                           PINY2885
0475         2953 FORMAT(1X,2A4,1H*,10X,27HROUTINE HELP CALLED.DIFF OF,F5.2,         PINY2890
                 *14H  MPH RESULTS./20X,48HACCEPT ANSWER BELOW ONLY IF DIFF LESS THAPINY2895
                 *N 0.50./20X,20HOTHERWISE DO BY HAND/)                              PINY2900
0476         4020 FORMAT(17X,15HWEAVE VOLUME OF,F6.0,27H PCPH YIELDS THE FOLLOWING:/PINY2905
                 *)                                                                  PINY2910
0477         4520 FORMAT(27X,15HWEAVE VOLUME OF,F6.0,27H PCPH YIELDS THE FOLLOWING:/PINY2915
                 *)                                                                  PINY2920
0478         6100 FORMAT(1H/,50X,25H***LAST CARD PROCESSED***)                       PINY2925
0479              STOP                                                               PINY2930
0480              END                                                                PINY2935
0001              SUBROUTINE SERVUL(NNW,SNW,NFLAG)                                   PINY2940
0002              COMMON/BLKA/NINPUT,N,SVTYP,PHF,VNW,SV                              PINY2945
0003              REAL NNW,PHF,VNW,SNW,SV,ARRA(5,3),ARRB(5),SPD(5)                   PINY2950
0004              INTEGER NINPUT,N,SVTYP                                             PINY2955
0005              DATA ARRA/700.0,1000.0,1500.0,1800.0,2000.0,800.0,1167.0,1600.0,  PINY2960
                 *1800.0,2000.0,850.0,1250.0,1600.0,1800.0,2000.0/                   PINY2965
0006              DATA SPD/60.0,55.0,50.0,38.0,30.0/                                 PINY2970
0007              NFLAG=0                                                            PINY2975
0008              IF(NINPUT.NE.0) GO TO 50                                           PINY2980
0009              I=N-2                                                              PINY2985
0010              IF(I.EQ.0) I=1                                                     PINY2990
0011              IF(I.GT.3) I=3                                                     PINY2995
0012              GO TO 60                                                           PINY3000
0013           50 I=2                                                                PINY3005
0014              IF(NINPUT.LE.2) I=1                                                PINY3010
```

TABLE F-8 (Continued)

```
      IF(NINPUT.GE.4) I=3
   60 CONTINUE
      DO 100 J=1,5
  100 ARRB(J)=ARRA(J,I)
      ARRB(3)=ARRB(3)*PHF
      ARRB(4)=ARRB(4)*PHF
C     SVTYP =1 IS GIVEN NNW FIND SV AND SNW
C            2    GIVEN SNW FIND SV AND NNW
      IF(SVTYP.EQ.1) GO TO 500
      STEMP=SNW
      IF(SNW.GE.SPD(1)) STEMP=60.0
      IF(SNW.GE.SPD(5)) GO TO 200
      WRITE(6,150) SNW
  150 FORMAT(50X,4HSNW=,F6.0,45H SPECIFIED...THIS STEP MODIFIED OR TERMI
     *NATED/)
      RETURN
  200 CONTINUE
      DO 250 I=2,5
      IF(SNW.GE.SPD(I)) GO TO 260
  250 CONTINUE
  260 CONTINUE
      DEL=(1.0/SPD(I)-1.0/SNW)/(1.0/SPD(I)-1.0/SPD(I-1))
      SV=ARRB(I)-DEL*(ARRB(I)-ARRB(I-1))
      NNW=VNW/SV
      RETURN
  500 SV=VNW/NNW
      IF(SV.LE.ARRB(1)) SV=ARRB(1)
      IF(SV.LE.ARRB(5)) GO TO 600
      WRITE(6,525) SV
  525 FORMAT(50X,3HSV=,F6.0,56H IMPLIED BY VNW GIVEN...THIS STEP MODIFIE
     *D OR TERMINATED/)
      NFLAG=1
      RETURN
  600 CONTINUE
      DO 640 I=2,5
      IF(SV.LE.ARRB(I)) GO TO 650
  640 CONTINUE
  650 DEL=(ARRB(I)-SV)/(ARRB(I)-ARRB(I-1))
      DELA=-DEL*(1.0/SPD(I)-1.0/SPD(I-1))+1.0/SPD(I)
      SNW=1.0/DELA
      RETURN
      END
      SUBROUTINE LANOUT(XLOUT,VPCPH,W,VLEG,SV)
      REAL XLOUT(7),VPCPH(4),W,VLEG(4),SV
      XLOUT(1)=VPCPH(1)/SV
      XLOUT(2)=W
      XLOUT(3)=VPCPH(4)/SV
      DO 100 I=4,7
      J=I-3
  100 XLOUT(I)=VLEG(J)/SV
      RETURN
      END
      SUBROUTINE HELP (WMAX,CONST,SNW,SW,DIFW)
      REAL PHF,VNW,SV,NNW
      INTEGER NINPUT,N,SVTYP
      COMMON/BLKA/NINPUT,N,SVTYP,PHF,VNW,SV
      DIFF=1000.0
      XN=N
      DO 500 I=1,61
      SVTYP=2
      SNW= 60.0-0.5*(I-1)
      CALL SERVOL(NNW,SNW,NFLAG)
      IF(NNW.GE.XN) GO TO 500
      W= XN-NNW
      IF(W.LT.WMAX) GO TO 200
      W = WMAX
      NNW=XN-W
      SVTYP=1
      CALL SERVOL(NNW,SNW,NFLAG)
      XLGWN=ALOG10(W/XN)
      SW=10.0**((XLGWN-CONST)/0.372)
      DIFW=0.0
      GO TO 400
  200 XLGWN=ALOG10(W/XN)
      SW=10.0**((XLGWN-CONST)/0.372)
      DELS=48.3-27.4*ALOG10(SW)-0.146*(12.5)
      SNWOUT=DELS+SW
      DIFW=ABS(SNWOUT-SNW)
  400 IF(DIFW.GT.DIFF) GO TO 500
      DIFF=DIFW
      SNWSTR=SNW
      SWSTR=SW
  500 CONTINUE
      DIFW=DIFF
      SNW=SNWSTR
      SW=SWSTR
      SVTYP=2
      CALL SERVOL(NNW,SNW,NFLAG)
      RETURN
      END
```

APPENDIX G

AN ANALYSIS OF THE WARD-FAIRMOUNT WEAVING SECTION

The Ward-Fairmount evaluation (7) is particularly interesting because the improvements could not be properly anticipated by HCM procedures. One would expect that the recommended procedure should have more utility in this case, particularly as it is configuration-conscious, and this appendix addresses the question.

DEFINITION OF THE SITE

The Ward-Fairmount study graphically illustrates the effect of lane configuration on weaving area operations. The section of I-8 in San Diego between Ward and Fairmount Avenues habitually experienced breakdown in level-of-service F flow. Improvements in flow were accomplished by means of two successive improvements:

1. Adding a lane to the off-ramp at Fairmount Avenue thereby creating a "through" lane for one weaving flow.
2. Breaking up the on-ramp into two successive on-ramps.

Although the total length of the weaving section was also increased, a major part of the improvement in conditions can be shown to be attributable to the configuration changes made.

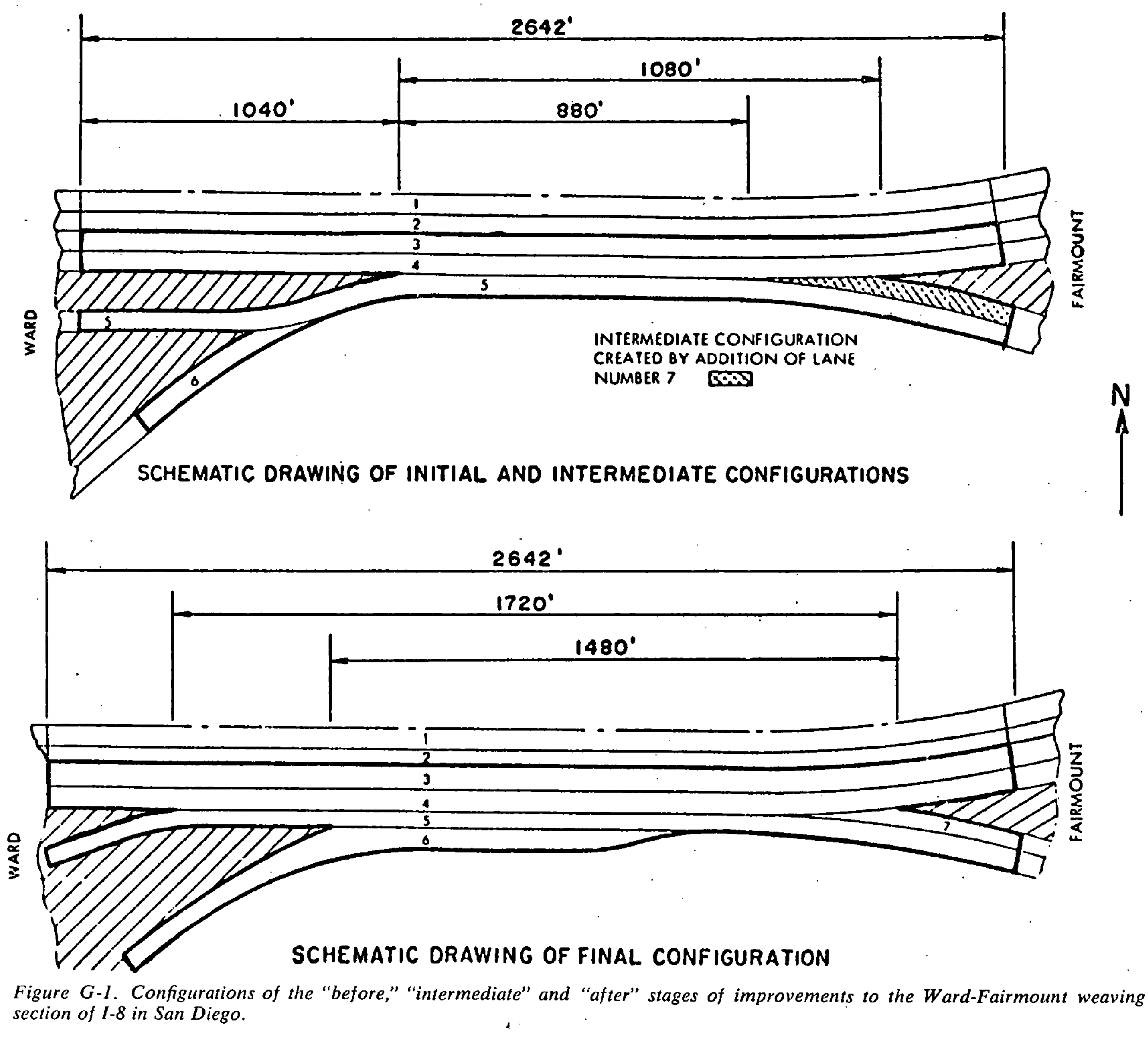
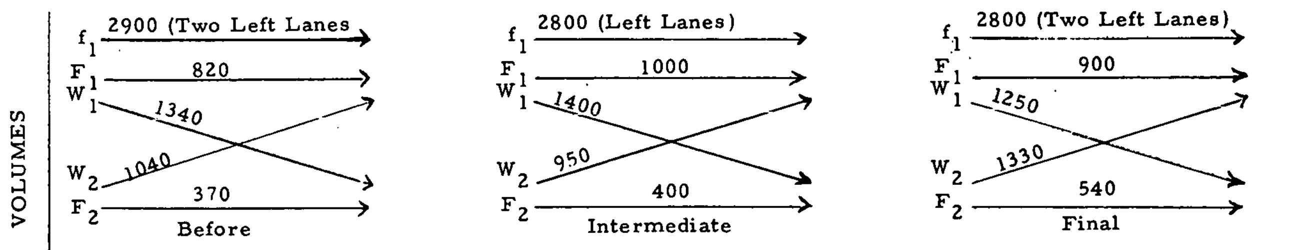


Figure G-1. Configurations of the "before," "intermediate" and "after" stages of improvements to the Ward-Fairmount weaving section of I-8 in San Diego.



QUALITY OF FLOW

	TRAVEL TIMES			AVERAGE NO. OF VEHICLES IN QUEUE	DELAY		AVERAGE SPEED (MPH)	OVERALL LEVEL OF SERVICE
	Average (seconds)	Standard Deviation (seconds)	Improvement (%)		Average (seconds)	Reduction (%)		
Before	63	10	--	15	19	--	28	F
Intermediate	54	11	14	10	10	47	33	E
Final	44	2	19	2	0	100	41	D

Figure G-2. Flow data for the three stages of the Ward-Fairmount study.

The configurations, as well as flows, for the "before," "intermediate" and "after" conditions are shown in Figures G-1 and G-2. Travel times, delays, and level of service are also included. The diagram shown in Figure G-1 was obtained from Reference 7; the data shown in Figure G-2 were obtained from Mr. K. Moskowitz of the California Division of Highways.

ANALYSIS

Two decisions were made in preparing the analysis:

1. Because of the speed data available, the two outer lanes were not included, either in terms of volume or lanes contributing to N.
2. Because of the $VR = V_w/V_{TOT}$, each of the three stages is considered a major weave.

Inspection of Figure G-1 yields lengths of 880 and 1,080 ft for the "before" and "intermediate" conditions, respectively. Consideration of the multiple weave guidelines—for that is what the "final" conditions may be considered—assigns all weaving to the 1,480-ft section. A summary of the results of the analyses is given in Table G-1. The speeds are compared in Table G-2.

It is possible that the "final" condition would be better, but this would require knowledge of the split of the on-ramp flows.

It is interesting that, if one considered the "before" condition as a ramp-weave, substantially better performance would have to be predicted, that is, $S_{nw} = 51$ mph and $S_w = 43$ mph. Leg Y, however, would require 1.3 lanes to cope with this. As it has only one lane, some backlog and related desegregation of the section would have to be expected. In fact, the field condition was characterized by heavy auxiliary lane queuing and the solution ("intermediate") was the addition of a lane to Leg Y. Such queuing is also implied in the speeds of the major weave analysis, particularly since the ramp-to-ramp flow is "locked in."

The section may also be analyzed with the full volumes and widths. This, however, requires separate manipulation of the speeds to be comparable to Table G-2; it also requires consideration of the VR in determining the applicable type. In fact, however, the concentration of vehicles is well accounted for in the above deletions in that lanes and their exact contents are deleted.

EVALUATION

The application of the recommended procedure reflects the observed conditions, but not exactly. Certainly, greater precision would be possible in the "after" condition if the on-ramp split were known. Still, an understanding of the recommended procedure causes one to look for and observe: (1) leg overloads, which lead one to increase lanes if necessary; (2) ramp-to-ramp flows being "locked in" by weaving flows; and (3) queueing resulting from low speeds and/or the previous two items. The pattern of the enhancement—some added length with an additional output lane, then added width with more additional length—yields analysis results that are comparable to the actual condition.

As noted, the HCM methodology, when applied to the same problem, fails to reflect the actual results, as it is insensitive to the critical element of lane configuration which is developed throughout this report. HCM Chapter 7 predicts level of service E operation for all three cases, with no further information.

TABLE G-1

ANALYSIS OF THREE STAGES OF THE WARD-FAIRMOUNT STUDY

```
PROBLEM TITLE:  WFOR-2 A                                          PROBLEM TYPE:  MAJOR WEAVE,ANALYSIS
*************                                                     ************

         ****************
         ***INPUT DATA***
         ****************

               MOVEMENT:     1      2      3      4

            VOLUMES(PCPH)   820.   1340.  1040.   370.     PCPH SPECIFIED...USER ASSUMED TO DO ALL CORRECTIONS EXCEPT PHF.

               PHF= 1.00

         *****************
         ***OUTPUT DATA***
         *****************

            WFOR-2 A  **THIS MAJOR WEAVE HAS W MAX AT    3.60
                           CAN CONFIGURATION PROVIDE IT?**

            WFOR-2 A  GREATER OF INPUT LANES NOT SPECIFIED...ONE LESS
                      THAN INTERNAL N IS ASSUMED FOR ANY VALUE OF N=3,4,5
                      TWO ASSUMED IF N=2,FOUR IF N=6

PROBLEM *  N *  L *LVL OF SER* SPEEDS  *CONFIG*  W  * DEL S *********VOLUMES(PCPH)***********LANE REQUIREMENTS******
TITLE   *    *    * NWE  WEA * NWE WEA *CONSTR*      *       *  1     2     3     4  * A-X WEA B-Y * LGA LGB LGX LGY*
**********************************************************************************************************************

WFOR-2 A* 3. *  8.6*  E      E * 33. 25. *  NO   * 2.4*   8. *  820. 1340. 1040.  370.* 0.4 2.4 0.2 * 1.1 0.7 1.0 0.9*
          *    *     *         *         *       *    *     *                          *             *                *
```

```
PROBLEM TITLE:  WFINT-2                                           PROBLEM TYPE:  MAJOR WEAVE,ANALYSIS
*************                                                     ************

         ****************
         ***INPUT DATA***
         ****************

               MOVEMENT:     1      2      3      4

            VOLUMES(PCPH)  1000.   1400.   950.   400.     PCPH SPECIFIED...USER ASSUMED TO DO ALL CORRECTIONS EXCEPT PHF.

               PHF= 1.00

         *****************
         ***OUTPUT DATA***
         *****************

            WFINT-2   **THIS MAJOR WEAVE HAS W MAX AT    3.60
                           CAN CONFIGURATION PROVIDE IT?**

            WFINT-2   GREATER OF INPUT LANES NOT SPECIFIED...ONE LESS
                      THAN INTERNAL N IS ASSUMED FOR ANY VALUE OF N=3,4,5
                      TWO ASSUMED IF N=2,FOUR IF N=6

PROBLEM *  N *  L *LVL OF SER* SPEEDS  *CONFIG*  W  * DEL S *********VOLUMES(PCPH)***********LANE REQUIREMENTS******
TITLE   *    *    * NWE  WEA * NWE WEA *CONSTR*      *       *  1     2     3     4  * A-X WEA B-Y * LGA LGB LGX LGY*
**********************************************************************************************************************

WFINT-2 * 3. * 10.8*  E      E * 34. 28. *  NO   * 2.3*   7. * 1000. 1400.  950.  400.* 0.5 2.3 0.2 * 1.3 0.7 1.0 1.0*
          *    *     *         *         *       *    *     *                          *             *                *
```

```
PROBLEM TITLE:  WFFIN-2A                                          PROBLEM TYPE:  MAJOR WEAVE,ANALYSIS
*************                                                     ************

         ****************
         ***INPUT DATA***
         ****************

               MOVEMENT:     1      2      3      4

            VOLUMES(PCPH)   900.   1250.  1330.   540.     PCPH SPECIFIED...USER ASSUMED TO DO ALL CORRECTIONS EXCEPT PHF.

               PHF= 1.00

         *****************
         ***OUTPUT DATA***
         *****************

            WFFIN-2A  **THIS MAJOR WEAVE HAS W MAX AT    3.60
                           CAN CONFIGURATION PROVIDE IT?**

PROBLEM *  N *  L *LVL OF SER* SPEEDS  *CONFIG*  W  * DEL S *********VOLUMES(PCPH)***********LANE REQUIREMENTS******
TITLE   *    *    * NWE  WEA * NWE WEA *CONSTR*      *       *  1     2     3     4  * A-X WEA B-Y * LGA LGB LGX LGY*
**********************************************************************************************************************

WFFIN-2A* 4. * 14.8* D2     D2 * 39. 35. *  NO   * 3.2*   4. *  900. 1250. 1330.  540.* 0.5 3.2 0.3 * 1.2 1.1 1.3 1.0*
          *    *     *         *         *       *    *     *                          *             *                *
```

TABLE G-2

COMPARISON OF SPEEDS (MPH)

STAGE	DATA FROM FIGURE G-2	ESTIMATED FROM TABLE G-1
Before	28	28
Intermediate	33	30
After	41	36

APPENDIX H

A LINEAR PROGRAMMING FORMULATION OF WEAVING SECTION PERFORMANCE

In Chapter 2, basic statistics on lane changing were reported using data from three of the sites filmed as part of this project. Considering the lane-change probabilities $p_{ij}(r)$, it was established for this site that

- There is no detectable trend of these probabilities with volume.
- There is no detectable change of the probabilities from segment to segment within the section.
- There is a distinction among probabilities depending upon whether the lane change was essential or nonessential to accomplish the weaving desired; this causes two probabilities p_e and p_{ne} to be defined for the section.

The first two results are consistent with results of a study conducted at Northwestern (*8*).

This linear programming formulation serves to demonstrate configurational effects in weaving sections as well as the importance of internal volume concentrations or "hot spots" in controlling the performance of a weaving section. These basic mechanisms are often the cause of the limitations which are properly built into the recommended macroscopic procedure.

The linear programming formulation assumes that the probabilities p_n and p_{ne} are not dependent on length, configuration, or volume. This is consistent with the microscopic data analysis reported in Chapter 2. The examples presented herein assume that p_e is not dependent upon direction of movement (movement AY versus movement BX). This is also consistent with the Chapter 2 results, although it is indicated therein that p_{ne} is dependent upon direction of movement.

Data are neither sufficient nor appropriate to indicate the "net effect" of a vehicle as it changes lanes, in terms of a vehicle equivalence factor. It is assumed herein that a lane-changing vehicle is counted in both "cell positions" (defined below) while lane changing. The model (i.e., the computer program) is now capable of changing this value so that parametric studies can be made, but this extension was not deemed merited. The model, even with this double-counting (which cannot be disproven microscopically, given the data available) and a moderately high p_e, reinforces the concepts of the macroscopic model and illustrates important basic mechanisms. The form but not the essence of the results herein would be modified somewhat by these refinements. Attention was turned to the macroscopic model.

CONFIGURATION DEFINES TRANSITIONS

Depending upon configuration, a specific lane change may be either essential (*e*) or nonessential (*ne*). A transition matrix is defined for a *given configuration* and for a *given pair of legs*. The transition matrix for the BX movement of Figure H-1 (A) is given by

$$P_{BX} = \begin{bmatrix} 1 & 0 & 0 \\ p_{ne} & (1-p_{ne}) & 0 \\ 1 & p_e & (1-p_e) \end{bmatrix} \qquad \text{(H-1)}$$

whereas for the configuration of Figure H-1 (B) it is

$$P_{BX} = \begin{bmatrix} 1 & 0 & 0 \\ p_e & (1-p_e) & 0 \\ 0 & p_{ne} & (1-p_{ne}) \end{bmatrix} \qquad \text{(H-2)}$$

with the matrices for the AY movement also different.

Define $\alpha = [\alpha_1 \; \alpha_2 \; \alpha_3]$ as the initial distribution of BX weaving vehicles and $\beta \; [\beta_1 \; \beta_2 \; \beta_3]$ as the final distribution. Note that

$$\beta = \alpha \, P_{BX}{}^N \qquad \text{(H-3)}$$

and β_3 is the flow that does not make a successful weave in the first case.

In an actual case, β_3 will force itself to make its desired move. The turbulence caused by this, however, is undesired. Thus, β_3 can be used as a figure of merit in designing the section: one may specify, for instance, that $\beta_3 < 1$ percent of the entering volume.

For the second case, the figure of merit would be $(\beta_2 + \beta_3)$. The two configurations are thus different both in the transition matrices and in the defined figure of merit.

THE DESIGN CONSTRAINTS

Let the figure of merit (the measure of forced vehicles) be denoted F. Note that F is dependent not only upon p_e and p_{ne}, but also upon the input distribution (defined by α_2 and

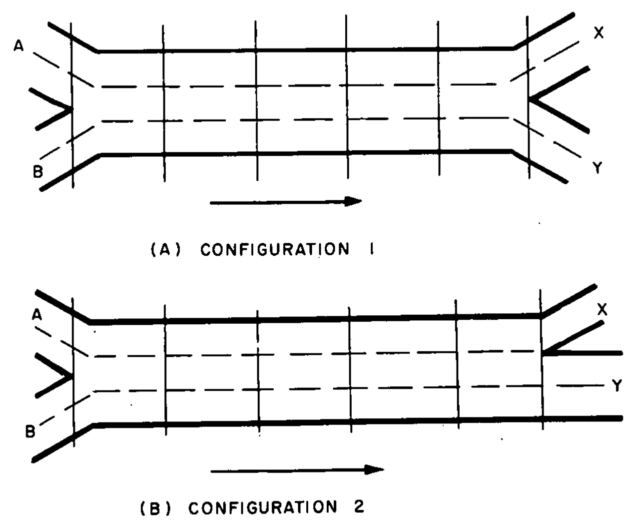


Figure H-1. Configurations studied in linear programming formulation.

α_3 since $\alpha_1 = 0$ by definition of the BX movement) and the number of subsections.

For a given distribution (say $\alpha_2 = 0.4$ and $\alpha_3 = 0.6$) and value of F (say 1 percent), one may compute the requisite number of subsection N to satisfy the figure of merit. This specifies length L since each subsection is to be 250 ft.

Note, however, that if the input value were doubled, the number of vehicles represented by β_3 (in the first case) would also double, but the percentage would not change. This is due to the linearity of the equations. It implies, however, that N need not change for increasing volume $V_B = (\alpha_2 + \alpha_3)$. This is contrary to observations, as noted in Figure H-2.

The percentage as a figure of merit is therefore unacceptable.

If one thinks of the absolute number of vehicles that miss a smooth weave (i.e., they are leftover), this defines the number of disturbances to occur at the end of the section. If one were to expect that the section could sustain no more than 1 or 2 such disturbances per minute, this defines the acceptable volume β_3.

$$F = \beta_3 \leq 60 \text{ or } 120 \text{ vph}$$

Note that for a given $V = V_o$, a length L_o is defined as before, say for $F = 60$ vph. For $V = 2V_o$ and this $L = L_o$, $\beta_3 = 120$ vph. Thus, L must be increased to decrease β_3 so that $\beta_3 \leq F = 60$ vph. Thus, the trend of Figure H-2 can be achieved.

A second consideration is that it is not permissible that the section break down internally. For a given level of service and input volumes, this means that in no lane in any subsection may the volume exceed the service volume (or some other critical value) for that level, as illustrated in Figure H-3.

Note that the volumes involved in Figure H-3 are not

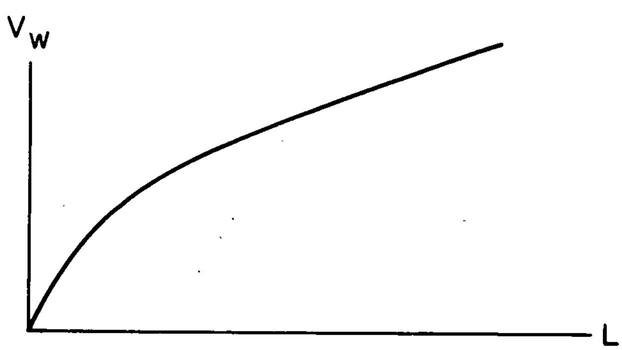


Figure H-2. Observed volume-length trend.

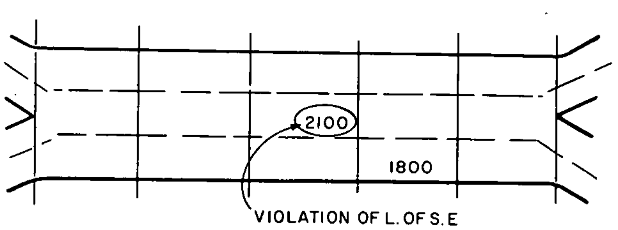
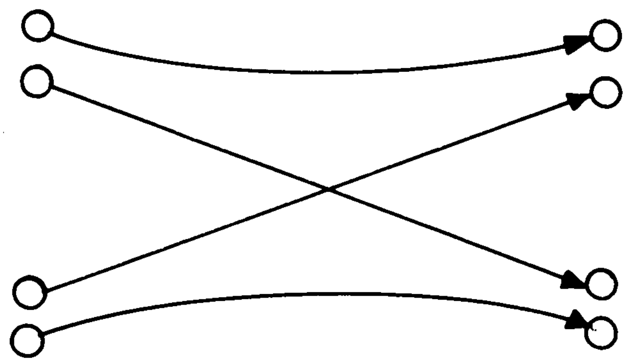


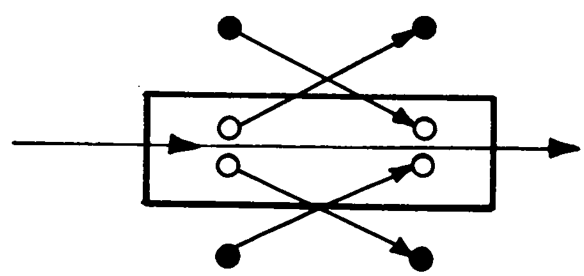
Figure H-3. Violation of internal volumes at level of service E.

simply contributions from leg B weaving traffic. There are two weaving and two nonweaving flows and *each* contributes.

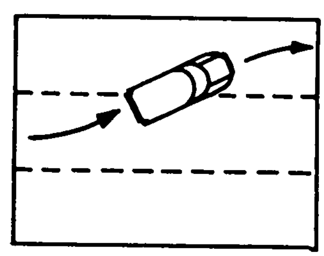


The problem is to find an appropriate length L for given input volumes such as to (1) satisfy the figure of merit F and (2) satisfy the constraints on lane volume.

In regard to lane volume, note that there are five components to this volume:



That is, there is (1) the traffic passing through the cell, (2) the traffic leaving it for other cells, (3) the traffic entering this cell. This implies that certain volumes will be counted in two cells within the same subsection. This is appropriate in a sense because vehicles do occupy two spaces while making their weaves:



Actually, one can argue that a vehicle should be counted 75 percent in each cell—or 1.5 vehicle equivalents—as it makes a weaving motion. This refinement can be incorporated, but is not included, in the examples herein.

THE LINEAR PROGRAM STATEMENT

Note that the weaving traffic in any cell (number of weaves as well as total weaving volume) may in principle be found for any input lane by use of the various transition paths and their associated probabilities. Refer to Figure H-4. For the second case defined above, the vehicles entering in lane 3 on the BX weave distribute as indicated.

Observe that in lane 2 of subsection 2 there is a volume count of (21 + 49 + 21) = 91 percent of input lane B2's weaving traffic. If the weaves were only counted fractionally, this would be ([¾] 21 + [¾] 49 + 21) = 73.5 percent.

Define v_{ir} to be the effective volume in lane i within subsection r. Then $v_{22} = 0.91\,\alpha_3 + 0.30\,\alpha_2 + \ldots$ in which α_3 refers to the BX weaving traffic entering from lane B2, α_2 to the BX weaving traffic entering from lane B1, and where there are add-on terms related to the AY weaving and the AX and BY through traffic. *The basic point, however, is that v_{ir} linearly related to the input volumes and the coefficients may be systematically determined.*

A program has been written to generate the set of coefficients for all volumes v_{ir} for any specified configuration and basic probabilities. This program requires a minimal input. The output is suitable for input to a standard linear programming package (IBM MPS).

The actual linear programming problem is to:

- Maximize the total weaving volume subject to the constraints of:
- Effective volume in every cell less than or equal to some specified service volume.
- Figure of merit on each of the weaving movements satisfied and perhaps to additional constraints.
- One weaving flow fixed, or the ratio of weaving flows fixed.
- Through vehicle flows specified, perhaps by lane.
- Distribution of vehicles by lane or within movements constrained; for example, $\alpha_2 \geqq \alpha_3$.

All of these constraints are linear, so that a standard linear programming problem exists.

The mechanism by which maximum volume is effected is a distribution by lane of each of the four section flows, subject to special constraints; a distribution result which yields maximum weaving volume and—as a byproduct—concentration patterns within the section. This distribution need not be unique: others may yield the same maximum weaving volume.

In any given problem, the number of subsections N is specified, as is the level of service being considered. By solving a set of such problems, one may observe the variation of weaving volume with length. One may thus generate information by which to evaluate any proposed configuration.

AN ILLUSTRATION

The two configurations of Figure H-1 were evaluated for $p_e = 0.7$ and $p_{nc} = 0.3$ over a range of lengths, with 60 vph used as the figure of merit on both weaving movements. The service volume constraints were obtained from HCM Table 9.1 for PHF = 1.00. For simplicity, zero outer flows were assumed. No constraint was placed on the ratio of weaving volumes.

It was observed in these particular cases that (1) the internal volume constraints rather than the "excess vehicles" figure of merit generally limited the capability of the section, (2) the critical points within the sections are the merge area and the center lane nearby, and (3) configuration did affect the capacity in all cases. As a consequence of the first item, the sections quickly became limited so that additional length did not improve capacity.

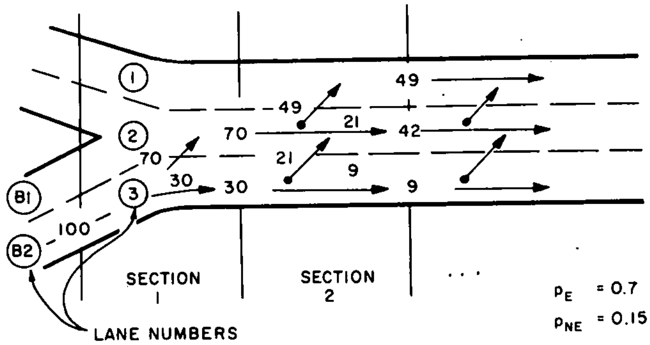


Figure H-4. Distribution of lane 3 vehicles in the BX weave.

Refer to Figure H-5, which illustrates the second case [Fig. H-1 (B)]. The volumes shown are *maximum* weaving volumes for the specified length and level of service; they may be decreased by certain minor-to-major weaving ratios.

Table H-1 summarizes the maximum weaving volumes for the two cases for a length of 1,500 ft. The first case, the more symmetric one, reaches its final levels (the plateaus of Figure H-5) virtually immediately.

Table H-1 also contains weaving volumes in this research, based on the HCM Chapter 7 procedure. The weaving ratio used in this is the one output in the linear programming solution for the second case [Fig. H-1 (B)].

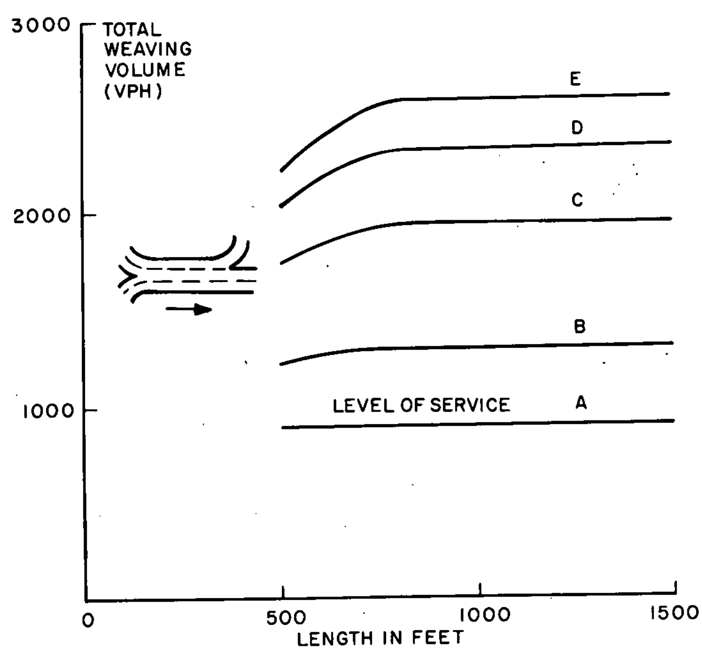


Figure H-5. Case study of weaving volumes.

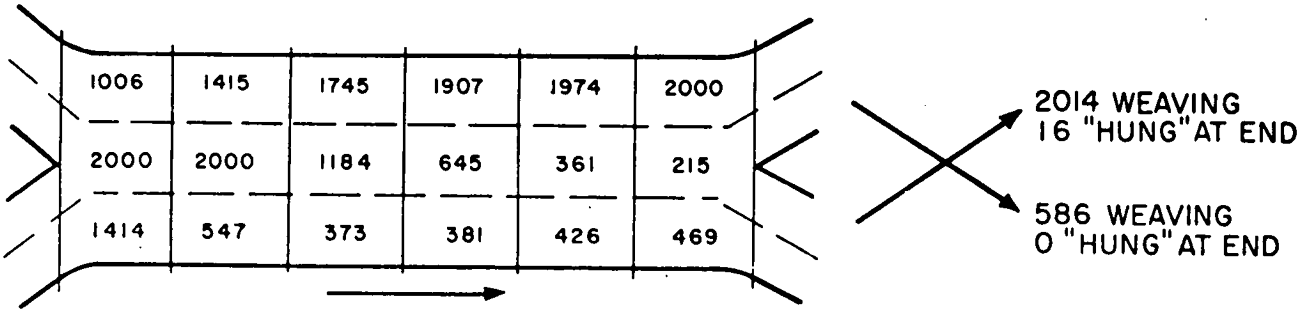


Figure H-6. Internal effective volumes for the first case under discussion.

Note: Volumes shown within the sections are effective volumes. Totals among subsections do not match because vehicles are counted in two cells at the place they weave.

TABLE H-1

MAXIMUM WEAVING VOLUMES FOR A LENGTH OF 1,500 FEET

LEVEL OF SERVICE	VOLUME (PCPH) FIRST CASE, FIG. H-1 (A)	SECOND CASE, FIG. H-1 (B)	PER HCM,[a] CHAP. 7 PROC.[b]
A	850	910	708
B	1,214	1,300	1,125
C	1,821	1,950	1,125
D	2,186	2,340	2,125
E	2,429	2,600	3,250

[a] Weaving Volume Ratio from "Second Case."
[b] Volumes for HCM procedures are for better quality of flow in each case where a range exists (HCM Table 7.3).

It is interesting that the linear programming approach predicts substantially lower capacity (level of service E) than the HCM procedure. Of course, the configurations considered would normally carry outer flows. This would both complicate the analysis and make it more realistic.

Figure H-6 illustrates the internal *effective* volumes for the first case at level of service E and 1,500 ft. Note that this section has critical points in the merge area and in the X-leg exit. The particular weaving volumes are not symmetric, but the section lane arrangement is. It happens in this case that a symmetric distribution of flows would also yield maximum weaving volume. This emphasizes that there may be a *range* of acceptable ratios of weaving volumes which yield maximum *total* volume, and only one value from this range is illustrated in the program output.

DISCUSSION

The results of this formulation do support the argument that configuration is a significant factor in weaving design. Evidence is given in Table H-1 and is shown in the little-used section segments in Figure H-6.

APPENDIX I

MULTIPLE WEAVE ANALYSIS

The weaving section that has occupied the major attention in this work is one in which two and only two traffic flows come together into one common roadway and then subsequently split apart into two and only two exit roadways. More complex weaving sections occur when more than two traffic flows come together and/or more than two exit roadway choices are available. This multiple weaving section can be seen in urban areas where, for example, two on-ramps enter an expressway upstream of an off-ramp. Some common types of multiple weaving section configurations are shown in Figure I-1.

THE HCM MULTIPLE WEAVE PROCEDURE

Multiple weaving sections are generally treated in the HCM as a sequence of subsections or segments for the purposes of analysis/design. Each segment is considered separately in terms of its length/width requirements. In design, the results of these individual treatments must, of course, be considered within the over-all context of lane arrangement and over-all design requirements.

The major problem in the HCM multiple weave design/analysis is in how to consider those weaving vehicles that traverse more than one segment. The position at which these vehicles execute their weaving maneuvers affects the over-all design/analysis results. The HCM has this to say about the problem of determining where weaving occurs:

> The manner in which weaving traffic divides itself between the various segments of a multiple weaving section can only be estimated. Considerable variation occurs, depending on geometrics, truck traffic, signing, and other factors. For purposes of analysis, it is considered reasonable to assume that weaving along the longer sections is proportional to the lengths of segments within these sections and thus allocate the weaving on that basis.

DATA AVAILABLE

BPR Data Base

Seventeen multiple weave experiments were provided by FHWA to the research agency at the initiation of the contract.

Use of the seventeen multiple weave experiments was hampered by several factors. Many of these experiments did not completely specify geometrics. In particular, many lengths were not included. Several of the experiments were of odd-type geometrics that did not conform to the multiple weave methodology as specified in HCM Chapter 7. These included overlapping simple weave sections consisting of an on-ramp followed by an off-ramp, another on-ramp, and another off-ramp, sections with three legs at one of the junctions, and sections with three or more segments, for which a methodology is not specified in HCM.

Only 4 of the 17 experiments, at two locations, include complete geometric data and conformed to the two-segment multiple weave analysis procedure of HCM Chapter 7. The locations were the southbound (Exp 55-56) and northbound (Exp 57-58) sections of the Schuylkill Expressway in Philadelphia, Pennsylvania, between City Line Avenue and Roosevelt Boulevard. Figure I-2 presents the geometric configurations for these two sites.

Even in these cases, the manner in which data were collected precluded as thorough an analysis as had been hoped for. Volumes and speeds were collected by movement through the entire weaving section and were not broken down by segment of the multiple weave.

Those weaving movements that could take place in more than one segment were not recorded so as to identify where they did take place. Thus it was impossible to evaluate the HCM assumption of weaving movements being proportional to segment length.

Project Data Base

In an effort to fill the gap in data, and particularly to enable evaluation of the "proportional allocation of weaving" hypothesis, attention was given in the project data collection to acquiring additional multiple weave site data. Information was to be required in sufficient detail to determine where weaving vehicles were executing their maneuvers. It was judged that a data collection procedure which enabled examination of individual vehicle trajectories through an entire multiple weave section was required. In terms of photographic data collection techniques, this meant that the total multiple weave section had to be visible in one frame

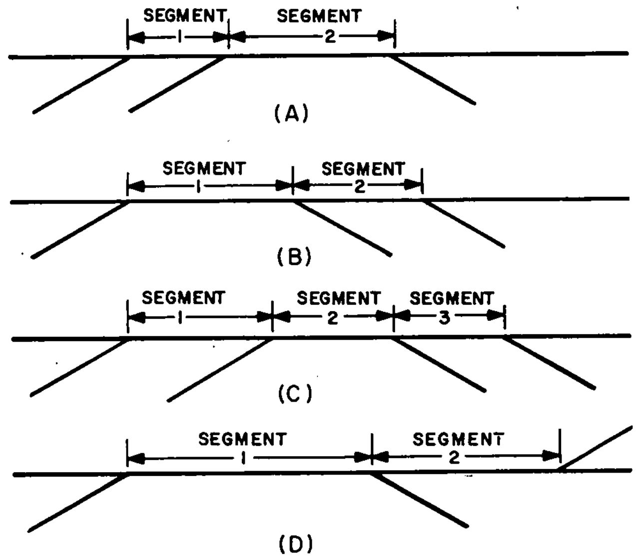


Figure I-1. Examples of multiple weave section configurations.

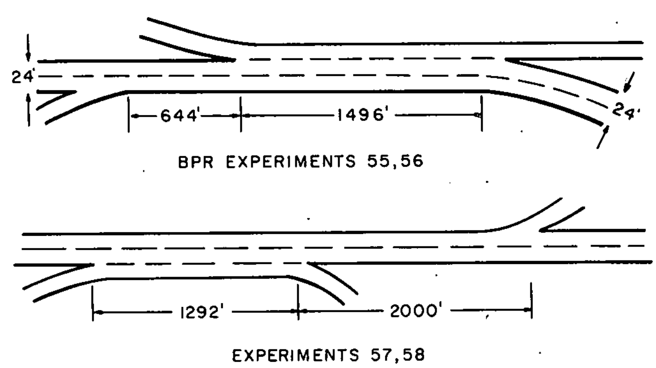


Figure I-2. Geometrics of usable multiple weave experiments.

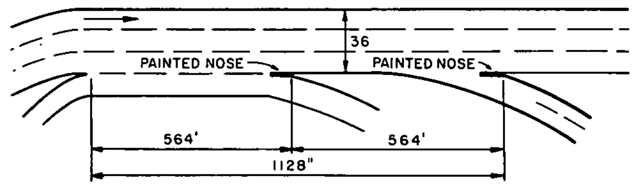
of a single-camera setup or within two frames of a two-camera setup. Two-camera setups of the type most often used to collect much of the project data base would not have been acceptable in that they frequently did not provide complete section coverage.

With these constraints, the problems of acquiring added multiple weave section data were great.

Use of helicopter-borne filming procedures was investigated in an effort to broaden the multiple weave data base. In terms of cost effectiveness ($12,000 to collect and reduce 30 min of data), this procedure was not considered to be feasible.

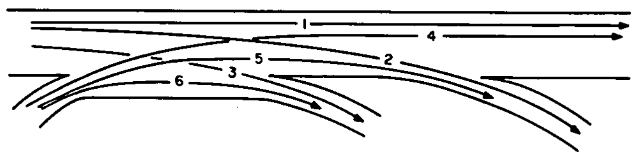
Comparatively few candidate multiple weave sections were available. Of those which were available, problems of vantage points for filming became critical. One site on the Fitzgerald Expressway in Boston was found that offered a sufficiently high adjacent vantage point to show the multiple weave section in one frame. The geometric configuration of this site is shown in Figure I-3 (A), with the movement definitions shown in (B) of the same figure.

As was originally planned, one multiple weave site was added to the (rather limited) available data base.



EXPERIMENT 4: FITZGERALD EXPRESSWAY N.B. NEAR CAUSEWAY STREET

(A) CONFIGURATION



(B) DEFINITION OF MOVEMENTS

Figure I-3. The geometric configuration and movement definitions of a multiple weave section.

CHARACTERISTICS OF THE PROJECT MULTIPLE WEAVE DATA

The two-segment multiple weave site shown in Figure I-3 is part of a three-segment multiple weave configuration of the two on-ramp/two off-ramp type. Although the entire three-segment weaving section did just fit into the picture, it was not possible to identify the position of vehicles at the entry point into the first segment.

Some three and one half hours of traffic movement through the multiple weaving section was filmed. In this time, slightly over 14,000 vehicle trajectories were recorded.

For each vehicle, data extracted from the film record included lane/leg of entry, lane/leg of exit, time at entry to segment 1, time of entry to segment 2, time at exit and lane changes (from lane x to lane y in quarter z).

Statistics were accumulated by 6-min periods for each movement [see Figure I-3 (B) for movement definition]. These statistics included numbers of vehicles both in actual vehicles and in passenger cars equivalent to movement, travel time (and thus speed) by movement within each segment. In addition, the lane placement of vehicles at the end of segment 1, at the mid-point of segment 2, and at the end of segment 2 is provided separately for each lane of entry. This lane placement information is precisely that required to enable evaluation of the "proportional weave" hypothesis.

Over the four-roll filming period at the multiple weave site, the section was observed to exhibit a broad range of operations, ranging from average speeds as low as 9 mph to as high as 40 mph. Figure I-4 presents the 6-min volumes and average speeds by segment for the entire film record. The speed decay experienced in the early portion of the filming was attributable to efforts downstream of the area of interest and outside of camera range.

ON THE PROPORTIONAL WEAVE HYPOTHESIS

If the assumption of the HCM is correct, it should be possible, given detailed data of the kind available, to observe vehicles making the "long weave" (movements 2 and 4) in both segment 1 and segment 2. Further, the number of such vehicles should be in proportion to the segment lengths.

Data from the first half of the experiment were considered unreliable for such an analysis in that the effects of shock waves moving back through the section might alter the desired behavior patterns of the users.

The 60 min of data defined as roll 4 in Figure I-4 was used as it presented a generally stable speed-volume picture with average speeds in the 35- to 40-mph range.

Before one can determine where weaving occurs, it is necessary to know how vehicles traverse the section. Figure I-5 shows the placement of the slightly more than 3,900 vehicles entering the section during the filming period defined as roll 4. The figure indicates the lane placement of vehicles at the end of segment 1 and at the middle and end of segment 2 by leg/lane of entry. Percentage distributions are also shown.

The most striking item of note is the small amount of lane changing that occurred in segment 1. Nearly all of the mainline vehicles entering the section in the median or center lanes were still in the same lane at the end of the first segment. Only the mainline curb lane had a substantial number of vehicles change lane by the end of segment 1, and this was the essential shift into the auxiliary lane in preparation for exiting the roadway.

Thus, in this case at least, there was absolutely no proportional allocation of weaving between the two weaving segments. All the weaving maneuvers associated with the second exit were undertaken in the second segment.

All the data for this site were examined to determine whether or not this almost total lack of lane changing was generally observed. Table I-1 indicates the percentage distribution of vehicles at the end of segment 1 by entrance lane for the slightly more than 14,000 vehicles filmed. One sees that the pattern of "staying in lane" occurs throughout the data and, therefore, that the proportional allocation hypothesis never holds. Under these conditions, the situation that in fact occurs is shown schematically in Figure I-6.

It is recognized that the total absence of proportional allocation of weaving in one case does not in itself invalidate the concept as presented in the HCM, this being only one experiment. The results are so extreme, however, that it is important to consider the ramifications of this in conjunction with the large amounts of presegregation observed,* not only in this experiment, but in all the filmed data collected by the researchers. The next section addresses an attempt to use the procedure developed in this research for multiple weave sections, based on the above-noted patterns.

GUIDELINES AND EXAMPLES FOR USE OF THE PROCEDURE ON MULTIPLE WEAVES

Although the data are very limited, the fact remains that the practicing engineer must cope with the design and analysis of multiple weave sections. It is therefore neces-

* The extent of presegregation—the proclivity of drivers to presort themselves—is truly remarkable. It is illustrated for the multiple weave in Figure I-5 and Table I-1.

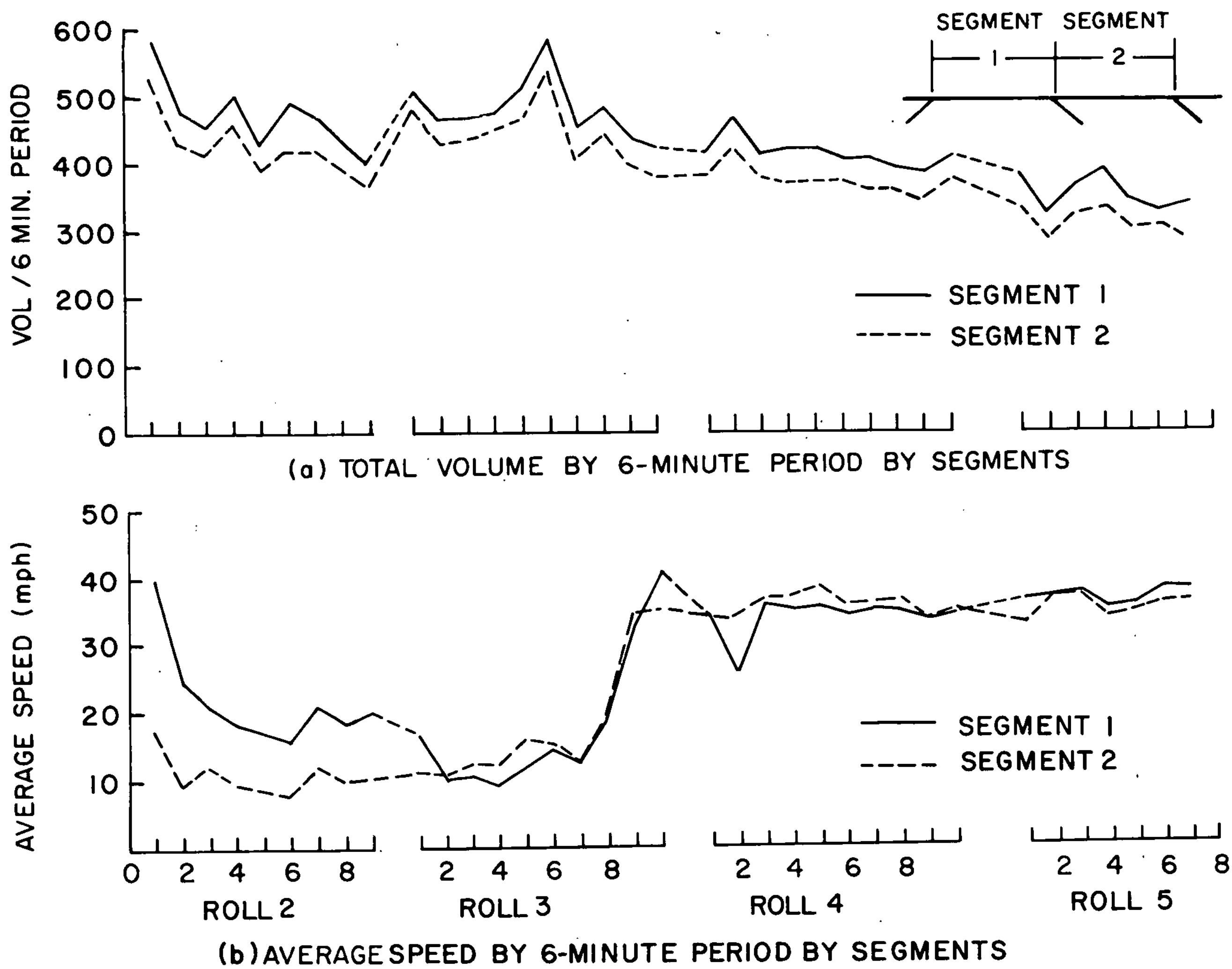


Figure I-4. Speed-volume characteristics of a multiple weave section.

sary that guidelines be developed out of the existing knowledge to the maximal extent possible and that the engineer be advised to use them with appropriate caution.

Three essential points exist:

1. A procedure has been developed, and it can be used effectively for the cases for which it was intended, as illustrated in Appendix D.
2. Intense presegregation holds for major weaves, ramp-weaves, and multiple weaves.
3. At least for the project multiple weave (Project Experiment 4), weaving movements are not proportional to subsection lengths in any sense, but rather are concentrated in subsections; the identification of the appropriate subsection can be done by consideration of presegregation and necessity.

To clarify this last point, consider movement 2 as shown in Figure I-6: By presegregation, movement 2 isolates itself from movement 3, and of necessity, it weaves in the second subsection. Presegregation holds by subsection.

After consideration of these points and investigation of the available experiments, the following guidelines are recommended:

1. Sketch the movements with consideration of presegregation and necessity to weave, so that the locations of weaves (and thus nonweaving and weaving volumes per subsection) are identified.

TABLE I-1

DISTRIBUTION BY PERCENT AT END OF SEGMENT 1
(entire experiment)

ENTRANCE LANE	NO. (%) IN EACH LANE			
	1	2	3	AUX.
1	99.9	0.1	—	—
2	—	97.6	—	2.4
3	—	—	69.0	31.0
On-ramp	—	—	87.0	13.0

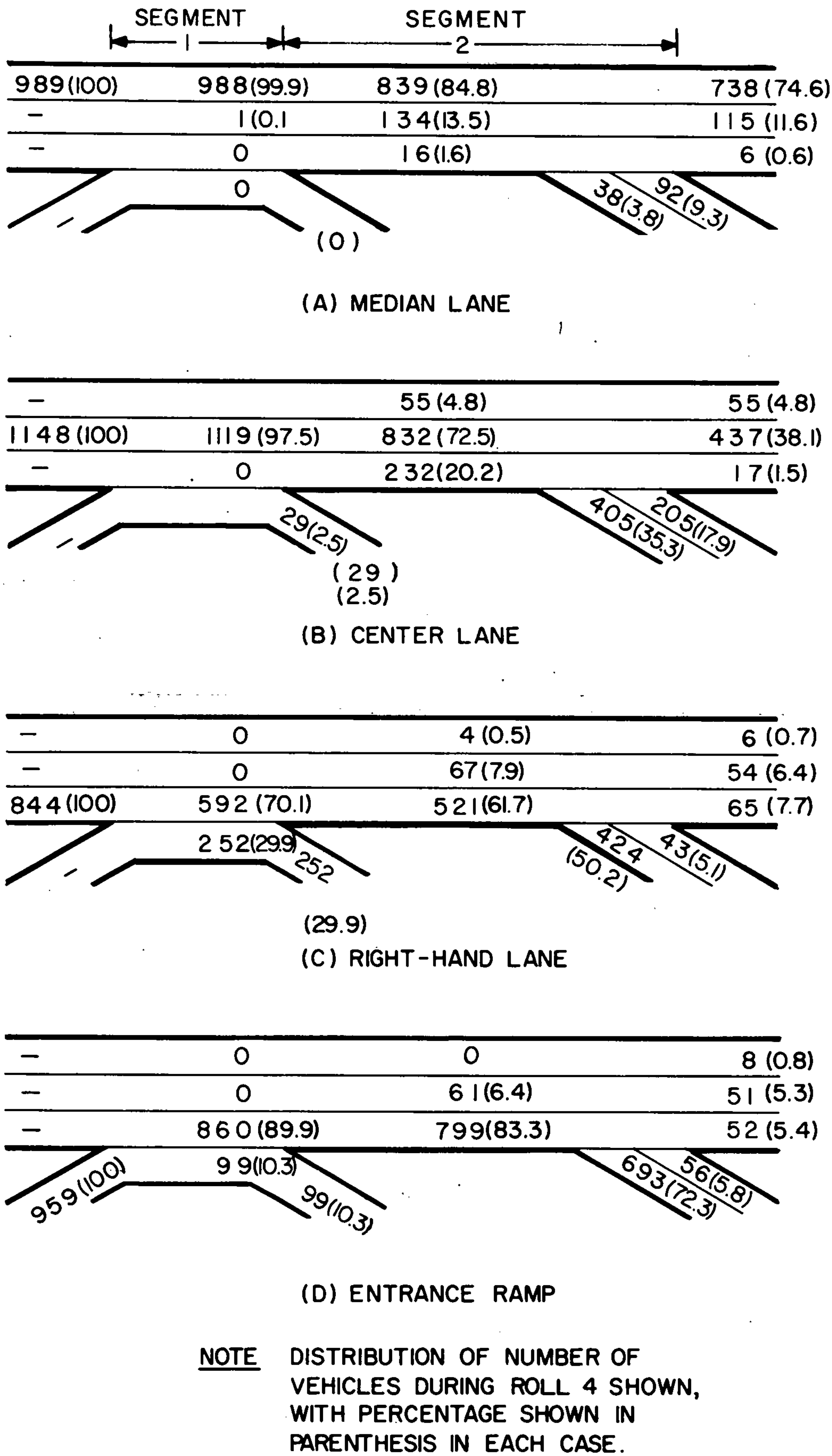


Figure I-5. Placement of vehicles in multiple weave section according to their entrance lane positions.

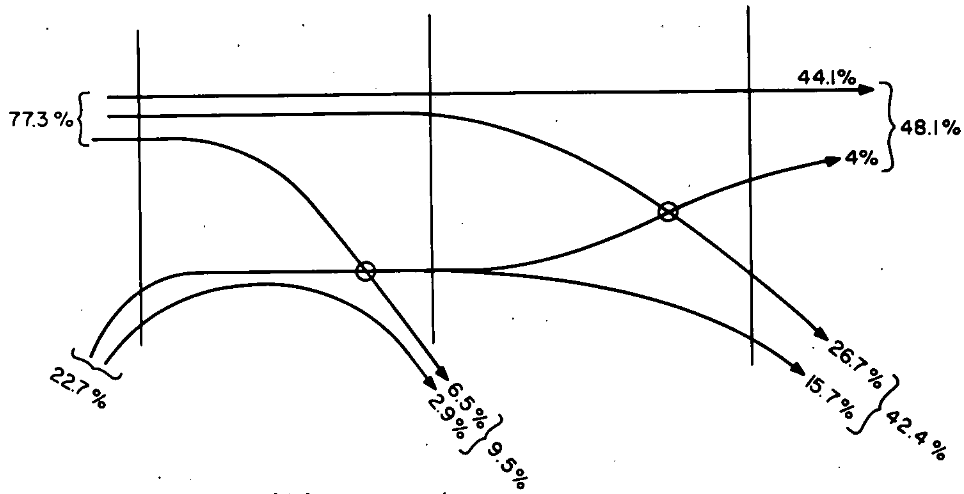


Figure I-6. Schematic of actual weaving maneuvers in a multiple weave section.

2. Classify the subsections as major weave or ramp-weave type.

3. Execute design or analysis as appropriate, subsection by subsection.

4. Review the over-all situation to determine whether there are any limiting conditions. For analysis, poor performance in a downstream subsection may control an upstream subsection. In design, lengths may have to be varied or width may have to be changed. In design, the subsection widths must be compatible and should provide lane continuity (Appendix C).

The available project and BPR multiple weaves are reviewed below according to these guidelines. Some insight and command of the procedure (Appendix E) is necessary.

Note that the guidelines recommend allocating each weaving flow to a single subsection, to be determined as above. Pending further research, this is the most appropriate recommendation.

Project Experiment 4

This experiment has been described in detail. Based on microscopic data, the movements are determined to weave as indicated in Figure I-6 and repeated in Figure I-7 (A). This, coupled with general presegregation patterns, is the basis for guideline 1.

The movements for each subsection are also identified in Figure I-7. On the basis of geometry and $VR = V_w / V_{TOT}$, the subsections are identified as a ramp-weave type and a major weave type, respectively. The lengths are given in Appendix II * as 564 ft for each.

The computer program of Appendix F is used to execute the computations for each subsection, for each 6-min period available. The speed data from the field work are manipulated so as to obtain weaving and nonweaving speeds per subsection according to the definitions of Figures I-7 (B) and I-7 (C). The results are shown in Figure I-8.

* Not included in this publication. See Appendix J herein for additional information.

The results indicated must be assessed with care:

1. It has already been noted that there was a downstream disruption that affected the early part of the data record (e.g., roll 2).

2. The analysis predicts an exceptionally poor S_w in subsection 2 during the roll 3 volume conditions. Since the range is so low (often 11 to 12 mph), one must expect level of service F to prevail for the entire flow. This is indeed what happens.

3. While the subsection 2 estimates are good for the roll 4 range (and less so for the roll 5 range), it must be noted that the last ramp is frequently overloaded in terms of internal (nonweaving) level of service. Twice, it would

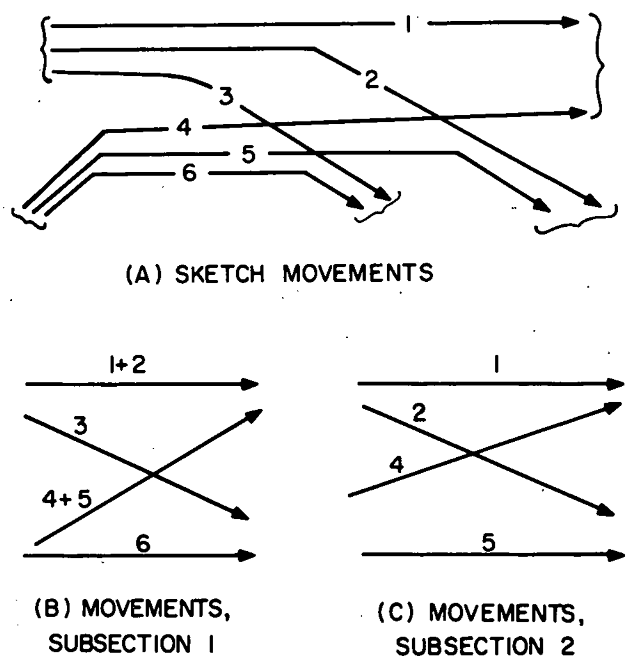


Figure I-7. Analysis of the weave movements shown in Figure I-6.

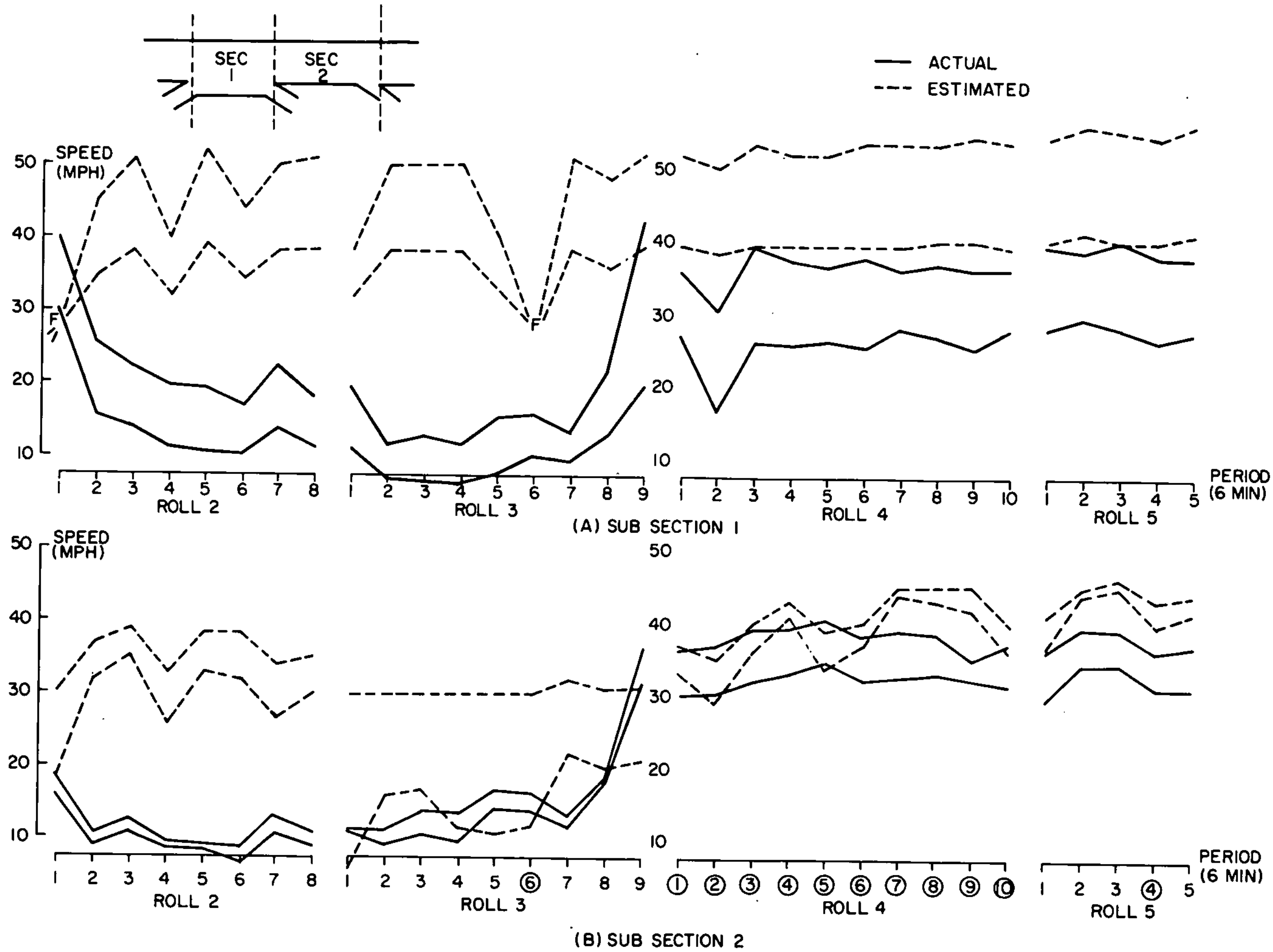


Figure I-8. Analysis to obtain weaving and nonweaving speeds per subsections (B) and (C) as shown in Figure I-7.
Notes:
1. In all sets, the S_{nw} curve is higher than the S_w curve.
2. The encircled period numbers indicate insufficient lanes on exist lane leg Y.

require 1.3 lanes. Some disruption can be expected, but not excessive.

4. It is estimated that subsection 1 will perform substantially better than subsection 2. The disruptions caused by vehicles continuing from subsection 1 to subsection 2 will adversely affect the performance of the former. If the S_{nw} therein limits the S_{nw} in subsection 1 to approximately 37 to 38 mph (e.g., rolls 4 and 5), the S_w therein would be 31 to 32 mph. (Actually, the observed S_w is somewhat poorer.)

With such care, it appears that the guidelines can be used effectively.

BPR Experiments 55 to 58

Four BPR experiments were identified as clearly multiple weaves as considered in the HCM. These are now considered.

Figure I-9 shows the movements and the division by subsection according to the recommended guidelines. These, in conjunction with the data given in Table I-2, allow estimation of the levels of service for each subsection via the procedure developed in this research. The two subsections for BPR experiments 55 and 56 are taken to be major weaves; the two for BPR experiments 57 and 58 are also taken to be major weaves. The first subsection of BPR experiments 57 and 58, geometrically a ramp weave, has a $VR = V_w/V_{TOT}$ sufficiently high that treatment as a major weave is more appropriate.

Figure I-10 summarizes the results of the speed analysis. For BPR experiments 55 and 56, the over-all speeds per subsection do not differ too significantly from the predicted values. The expected ΔS's are not realized, however. BPR experiment 57 operates significantly better than expected. BPR experiment 58 has quite comparable volumes to BPR experiment 57 and, thus, comparable estimates of performance, but it actually performs much poorer than either the estimate or the actual levels of BPR experiment 57. One

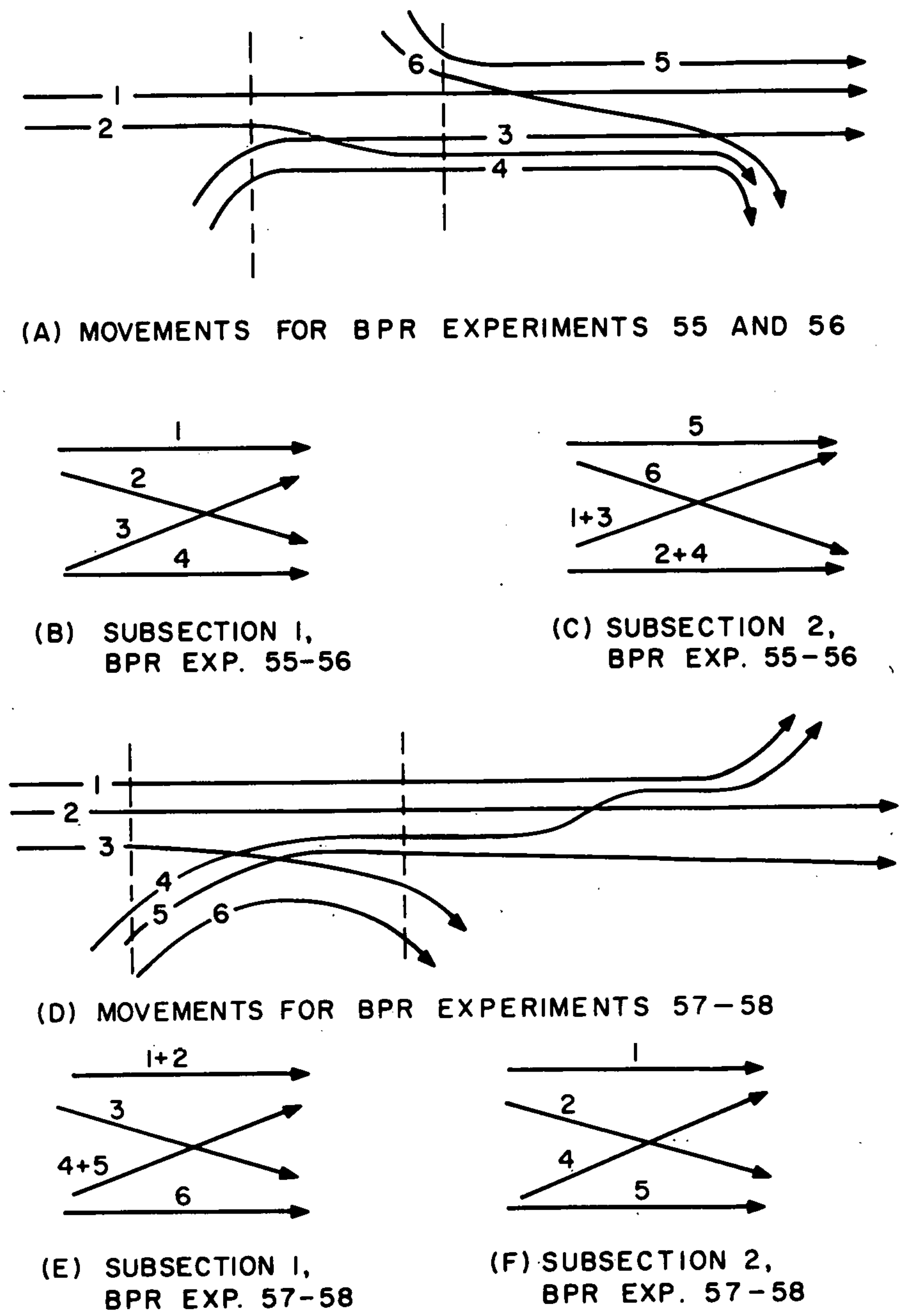


Figure I-9. Weaving movements of BPR multiple weave experiments 55 through 58.

TABLE I-2

DATA (HOURLY) FOR BPR EXPERIMENTS NO. 55–58

MOVEMENT	VOLUME (VPH) NO. 55 PASS.	NO. 55 COMM.	NO. 56 PASS.	NO. 56 COMM.	NO. 57 PASS.	NO. 57 COMM.	NO. 58 PASS.	NO. 58 COMM.	SPEED (MPH) NO. 55	NO. 56	NO. 57	NO. 58
1	792	85	825	65	337	14	344	20	30	24	34	22
2	1900	144	1986	155	1962	132	1962	82	29	25	37	21
3	783	2	753	8	703	29	507	21	20	17	37	—
4	158	8	239	15	570	11	481	13	20	18	34	19
5	52	3	63	8	625	51	740	53	—	—	38	27
6	985	7	872	35	3	0	24	2	36	36	—	—

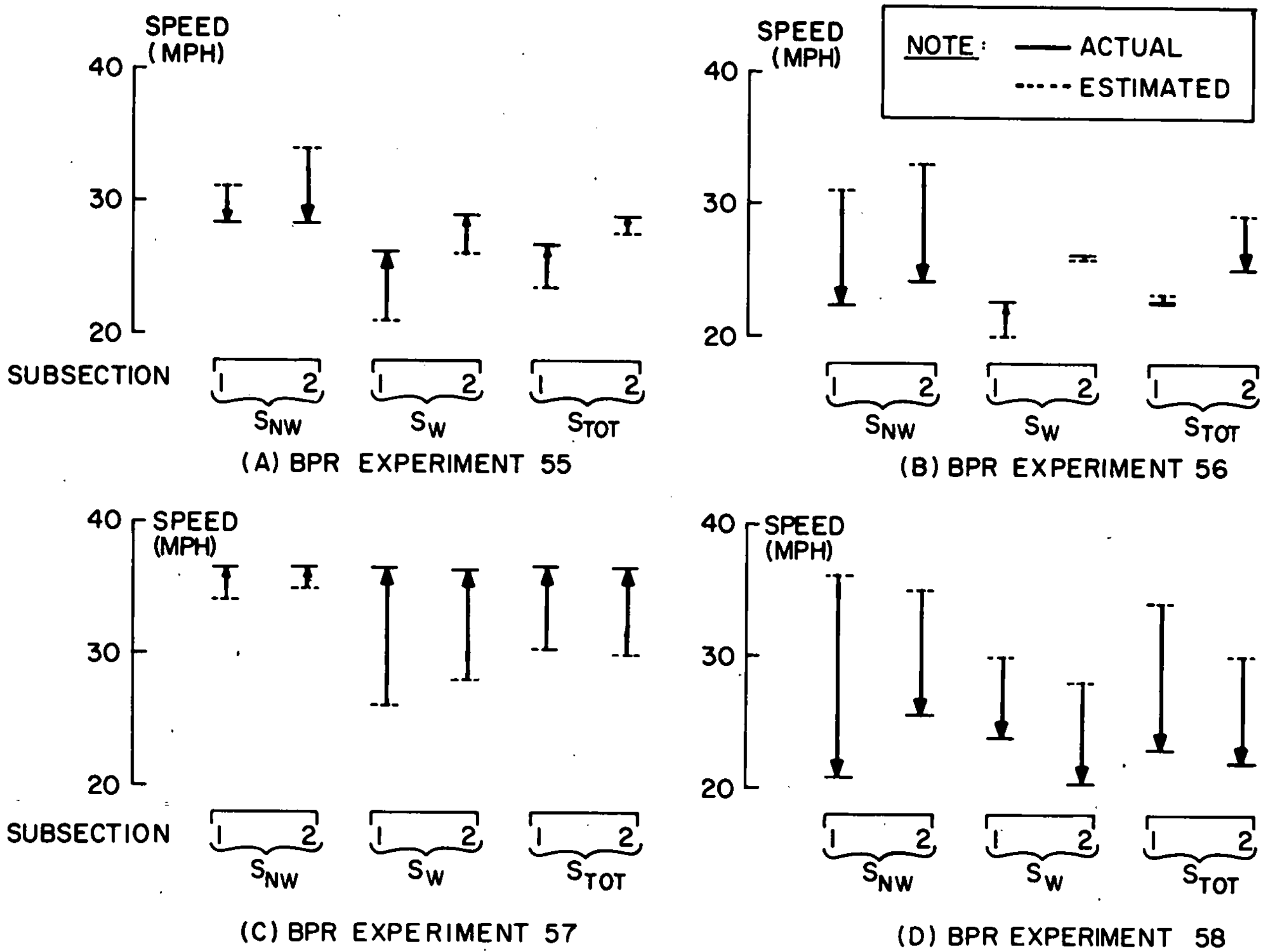


Figure I-10. Speed analysis for the BPR experiments 55 through 58.

can only deduce there were external factors—perhaps a downstream disruption—that controlled during this period. As with the other three BPR experiments, information is not available to investigate such insights. Considering the available data, BPR experiment 58 is discounted and the guidelines are judged to have reasonable utility.

APPENDIX J

UNPUBLISHED MATERIAL

Several appendices contained in the report as submitted by the research agency are not published herein. Their titles are listed here for the convenience of those interested in the subject area. Qualified researchers may obtain loan copies of any or all of the items by written request to the Program Director, NCHRP, Transportation Research Board, 2101 Constitution Avenue, Washington, D.C. 20418.

The titles are:

1. Appendix I—The Urban Weaving Area Capacity Study and the Ramps Data Base.
2. Appendix II—Project Data Base.
3. Appendix IV—Analyses Related to the Structure of the HCM Procedures.

4. Appendix V—Accuracy and Consistency of the HCM Procedures.
5. Appendix XIV—Extensions to the Weave and Ramp Computer Programs Developed by ITTE.
6. Appendix XV—Aspects of the Regression Procedure Data Base.
7. Appendix XVI—Gowanus Expressway Aerial Data Collection.

Appendix III and Appendices VI through XIII of the original report have been published herein as Appendices A through I.

The unpublished appendices have not been edited; thus, none of the roman numeral references to them within the published text have been altered in the editorial process so that accuracy of cross references can be retained.

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2	An Introduction to Guidelines for Satellite Studies of Pavement Performance (Proj. 1-1), 19 p., $1.80
2A	Guidelines for Satellite Studies of Pavement Performance, 85 p.+9 figs., 26 tables, 4 app., $3.00
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* Highway Research Board Special Report 80.

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