STUDIES OF WEAVING AND MERGING TRAFFIC

A SYMPOSIUM

•

WEAVING PRACTICES ON ONE-WAY HIGHWAYS
by F. HOUSTON WYNN

MERGING TRAFFIC CHARACTERISTICS APPLIED TO ACCELERATION LANE DESIGN
by STEWART M. GOURLAY

A STUDY OF MERGING VEHICULAR TRAFFIC MOVEMENTS
by RICHARD I. STRICKLAND

TECHNICAL REPORT NO. 4
BUREAU OF HIGHWAY TRAFFIC
YALE UNIVERSITY

Published with funds from
ENO FOUNDATION FOR HIGHWAY TRAFFIC CONTROL
1948

THE YALE HIGHWAY TRAFFIC SERIES

Technical Report No. 1 — *Traffic Performance at Urban Street Intersections,* by Bruce D. Greenshields, Donald Schapiro, and Elroy L. Ericksen.

Technical Report No. 2 — *Toll Bridge Influence on Highway Traffic Operation,* by M. Earl Campbell.

Technical Report No. 3 — *An Economic Study of Interior Block Parking Facilities,* by Charles S. LeCraw.

Technical Report No. 4 — *Studies of Weaving and Merging Traffic,* A Symposium, by F. Houston Wynn, Stewart M. Gourlay, and Richard I. Strickland.

FOREWORD

This is the fourth in a series of technical reports to be issued by the Bureau of Highway Traffic. It is the first which combines a group of theses concerned with similar traffic characteristics.

These theses were prepared as the result of original research by graduate students at the Bureau of Highway Traffic. A certain amount of editing to eliminate duplicative material and the preparation of the general statement of objectives and methods included in the Preface were performed by Mr. Edmund R. Ricker of the Bureau staff. The technical data, analysis, and conclusions are the work of the student authors.

The Bureau of Highway Traffic is indebted to the Eno Foundation for Highway Traffic Control, Inc., for making funds available for publication of the technical series.

THEODORE M. MATSON, *Director*
Bureau of Highway Traffic
Yale University

TABLE OF CONTENTS

TABLE OF CONTENTS

(Continued)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES

LIST OF TABLES

LIST OF TABLES

PREFACE

A method for more thorough analysis of vehicular traffic movement has been made available in recent years by the application of the theory of probability. Earlier work by Kinser[1] and Adams[2] was reviewed and given broader scope in the research described in the first report of the Yale Technical Series, "Traffic Performance at Urban Street Intersections."[3] In that research the probability theory, together with a photographic technique of obtaining data on moving traffic, was used in the study of the characteristics of intersecting traffic streams.

There are numerous other applications of the photographic technique and probability theory to everyday traffic problems. Student research at the Bureau of Highway Traffic has naturally followed an extension of these methods into a variety of such problems, due partly to the inspiration of the earlier work and also to the availability of the photographic equipment assembled by Dr. Greenshields. The three theses reproduced in this report have as a common interest the determination of the time gap in a moving traffic stream which is required for the intermingling of vehicles from an adjacent lane or stream.

The concept of acceptable time gaps is a very useful one. The flow and intermingling of traffic depend to a large extent upon the action of individual drivers. Each motorist has formed a judgment, based on his own driving experience, of the opening between two successive moving cars which is adequate for him to enter safely and comfortably, under given conditions of roadway and speed. It is presumable that this judgment is made in terms of *time* rather than *distance*, since the gap is actually moving along the highway, and the motorist's weaving or merging maneuver depends on his own speed, as well as that of the limiting cars. The determination of the time gap acceptable to a large group of motorists under various

---

[1] John P. Kinzer, "Application of the Theory of Probability to Problems of Highway Traffic." Student thesis, Brooklyn Polytechnic Institute, 1933. Reviewed by Prof. Lloyd F. Rader, *Proceedings of the Institute of Traffic Engineers,* pp. 118-123, 1934.

[2] William F. Adams, "Road Traffic Considered as a Random Series," *Journal of the Institution of Civil Engineers,* pp. 121-130, 1936.

[3] Bruce D. Greenshields, Donald Schapiro, and Elroy L. Ericksen, *Traffic Performance at Urban Street Intersections,* Technical Report No. 1, Bureau of Highway Traffic, 1947.

traffic conditions should supply fundamental data for the design of highways to best accommodate the road users.

Measurements of acceptable time gaps under actual traffic conditions are easily and accurately made by the photographic method. The equipment developed for this purpose is described in Technical Report No. 1.[4] It consists of a 16 mm. movie camera, an electrically driven counter, and a timing mechanism, set to operate the shutter and counter at a rate of 88 pictures per minute. The camera is placed in a position from which its field of view includes a section of roadway on which the particular movement to be studied is occurring. To observe a roadway of sufficient length, the camera location must be chosen at a point considerably above the roadway and not too distant laterally. The portion of highway to be studied is prepared by laying down a series of regularly spaced white markings at intervals of 10 to 50 feet, depending on the range from the camera. When the resulting pictures are projected, these markings may be used to draw a grid in the proper perspective to directly measure the location of each car in a sequence of frames showing its movement throughout the field of view. The relative location of a car on succeeding frames can be used to determine its speed, movement relative to other cars or fixed objects, and the time and distance utilized to perform various traffic maneuvers.

The application of the theory of probability, or Poisson's Law, depends upon the individual vehicle being placed at random in time and space; i.e., that the traffic is free-flowing, is not congested, and is not subject to artificial interference, such as limiting sight distance or police control.

Within the scope of the studies made to date, it has been found that there are definite upper limits to traffic volumes at which vehicles will be distributed purely at random. For two-lane roads, on which higher volumes cause a bunching of traffic because of inability to pass, the limiting volume appears to be 200 vehicles per lane per hour (400 vehicles per hour for the two directions).[5] On multi-lane roadways, where freedom of passing is provided, the limiting volume is about

---

[4] *ibid.*, p. 1.
[5] *ibid.*, p. 77.

1000 vehicles per lane per hour.[6] However, this does not severely restrict applications of Poisson's Law as suggested by the present authors, first, because they are considering multi-lane roadway design, and secondly, because the occurrence of the larger gaps (say six seconds) is less affected by the bunching of vehicles. Until further experimental data are available, considerable caution must be exercised in extrapolating beyond these volumes.

Under conditions which allow random placement of vehicles, the frequency of occurrence of time gaps of a given size, or larger, can be computed from the Poisson equation expressed in the following form:

$$P = e^{-\frac{tv}{3600}}$$

Where P = per cent of time gaps equal to or greater than "t" seconds

t = acceptable time gap in seconds
v = number of vehicles per lane per hour
e = base of Naperian logarithms = 2.71828

The relationship between volume and frequency of occurrence of time gaps of various lengths is shown in Figure 1. The number of openings of a given duration, or longer, can be obtained by entering the chart at the appropriate volume and reading the per cent of openings corresponding to the acceptable length of time gap; multiplication of this per cent of openings by the traffic volume will equal the minimum number of opportunities of acceptable length for merging at a single point during an hour. The frequency with which the drivers of merging vehicles will be able to execute a desired maneuver requiring that length of time gap at the instant they wish to do so is also indicated by the percentage figure.

Mr. Wynn's thesis is concerned with the weaving movement of vehicles overtaking other vehicles on a multiple-lane one-way roadway. He has considered two types of weaves—*optional*, wherein the driver changes lanes at his own convenience, and *forced*, which are necessitated by an artificial blocking of one travel lane. Further subdividing into classes of weaves according

[6] Adams, *op. cit*, p. 129.

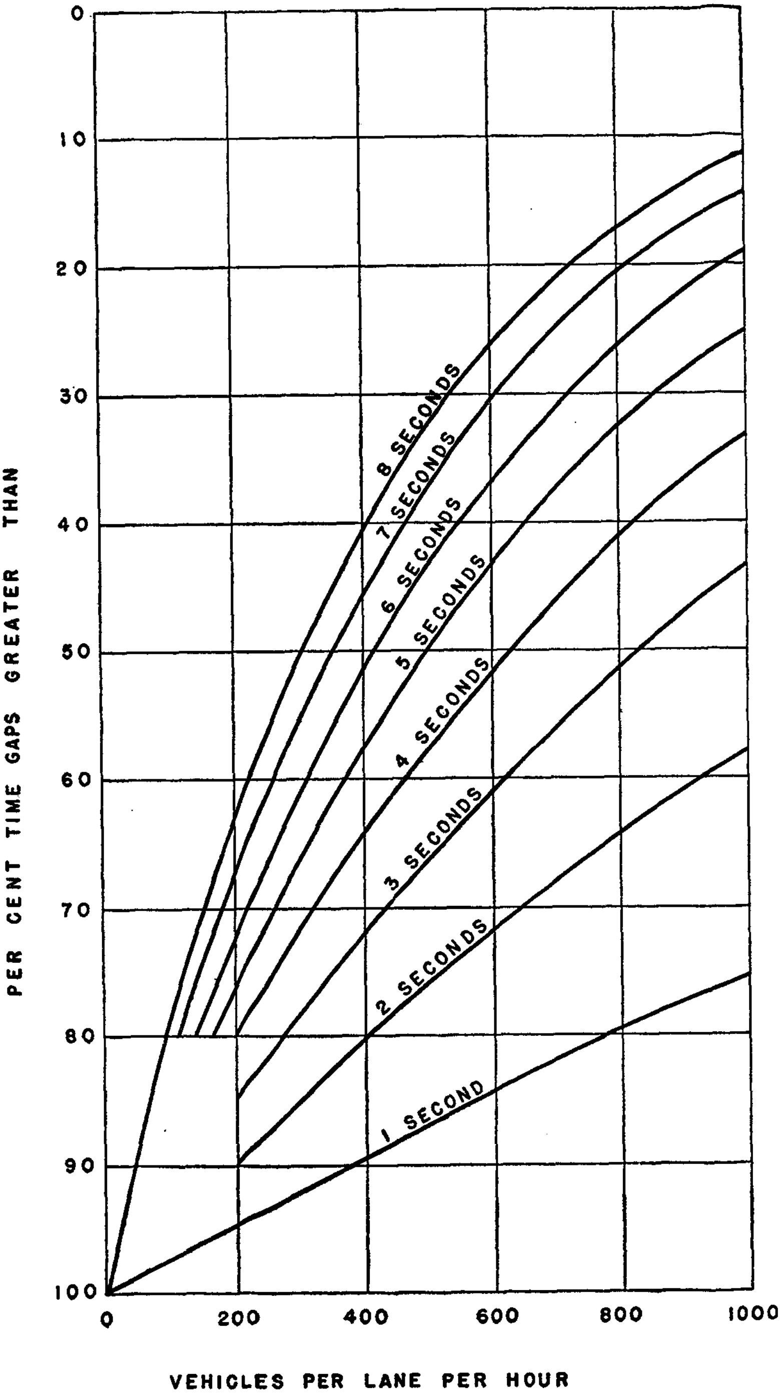

FIGURE 1—Frequency of Occurrence of Time Gaps of a Given Length or Greater

to the amount of interference from other moving vehicles, he has analyzed the length of weaves, amount of lateral movement, spacing of vehicles, and speeds of all vehicles involved. Within the limitations of his data, he has drawn significant conclusions as to the time required for weaving and the acceptable time gap between vehicles.

Mr. Gourlay has studied the merging of vehicles into moving traffic streams at locations where entering traffic is controlled by a stop-sign and where it is allowed to merge freely. He has determined tentative values of acceptable time gaps for these two conditions, and pointed out their implications in the design of acceleration lanes.

Mr. Strickland has extended the study of merging movements at non-stop locations to traffic circles. He has drawn comparisons with the results of the other two studies and shown values as measured for acceptable time gaps. He has modified the photographic technique and successfully applied it to the study of traffic movements at night.

EDMUND R. RICKER
Research Assistant in Transportation
Bureau of Highway Traffic
Yale University

WEAVING PRACTICES

ON

ONE-WAY HIGHWAYS

By

F. HOUSTON WYNN

A Thesis

Submitted to

BUREAU OF HIGHWAY TRAFFIC

YALE UNIVERSITY

May 1946

Mr. Wynn is at present employed as Highway Planning Survey Director with the Territory of Hawaii, Department of Public Works.

ACKNOWLEDGMENTS

This paper has been undertaken in an effort to gain background experience in the field of original traffic research. Without the untiring assistance and instruction of Professor T. M. Matson, Dr. Bruce Greenshields, and Mr. Donald Schapiro, the job could not have been done.

Thanks are also due Mr. Nathan Cherniak and the Port of New York Authority for interest and cooperation shown in making available facilities at the George Washington Bridge. I should like to express appreciation to the Riverside Church authorities, too, for granting permission to use the church tower as a base of operations.

Much credit for assistance in collecting data must go to Mr. Stewart Gourlay for his collaboration on field studies.

F. Houston Wynn

Yale University
May 1946

CHAPTER I

STATEMENT OF THE PROBLEM

Purpose of the Study

Weaving is one of the fundamental acts of driving in traffic which every driver on our streets and highways practices continually, yet very little scientific information is available on the subject. The study of weaving movements has been chosen as a topic for this paper with the hope that research students may find the method outlined herein a practical guide to further investigations in a subject that deserves considerable attention.

A "weave" as defined for purposes of this study is the movement of a car from one lane to the next adjacent lane. The presence of other vehicles complicates the procedure of the weaving vehicle, frequently retarding or hurrying its crossover and limiting its range of lateral movement. The amount of this type of interference is a basic factor in determining the frequency with which weaves can be made at any particular location.

An attempt has been made in this study to learn as many things as possible about weaving movements as they actually occur on the road. Because the study is limited to two sites and two hundred observations of weaving cars, the establishment of definite rules regarding the behavior of weaving traffic must await more adequate sampling at a variety of locations.

From studies of weaving movements it should be possible to determine the length of roadway necessary for vehicles making weaves under a variety of conditions of interference, speed differential, direction of weave, and volume of weaving traffic. The time necessary for completion of the weaving maneuver and the size of traffic opening that the driver of a weaving vehicle will accept are the basic elements in determining frequency of opportunity to weave. The findings of this paper show tentative values for these factors.

Previous Studies

Most of the research work undertaken with regard to study of weaving movements has been of a general nature and has been concerned primarily with passing habits or highway capacities.

Professor S. M. Spears[7] observed crossover distances from a moving car and developed a formula for application of his findings to design problems. This study did not take into account fluctuations in the volume of passing traffic and the consequent effect upon opportunities to weave across a parallel lane of moving traffic. His method of collecting data is dependent upon the judgment of the recorder and there is no opportunity to check the data collected, as may be done in the photographic method.

The time and distance requirements for overtaking and passing on two-lane roads were studied by Matson and Forbes.[8] A photographic method was used in which a series of snapshots recorded the position of the passing car relative to the test vehicle and distances were computed by stadia methods. A stop-watch was employed to determine the time of the passing maneuver. Again, the method of collecting data did not allow rechecking or cross-analysis with other factors.

The Public Roads Administration has carried out extensive studies on passing practices in connection with work on highway capacity. Results were published by O. K. Normann in 1939 and 1942[9] and C. W. Prisk in 1941.[10] A system of pressure-sensitive rubber tube detectors was placed across the roadway at fifty-foot intervals and connected to a moving-tape recorder. Thus, a complete record of speed, headway, and lateral movement was made for each vehicle.[11] Appropriate analysis of this type of data could obviously produce additional findings relating to weaving practices.

---

[7] S. M. Spears, "Psychological Factors in Highway Design and Traffic Control Problems", *Proceedings Highway Research Board,* Vol. 21, pp. 207-220, 1941.

[8] T. M. Matson and T. W. Forbes, "Overtaking and Passing Requirements as Determined from a Moving Vehicle", *Proceedings Highway Research Board,* Vol. 18, Part I, pp. 100-112, 1938.

[9] O. K. Normann, "Results of Highway Capacity Studies," *Public Roads,* Vol. 19, pp. 225-232, 1939; Vol. 23, pp. 47-81, 1942.

[10] C. W. Prisk, "Passing Practices on Rural Highways," *Proceedings Highway Research Board,* Vol. 21, pp. 366-378, 1941.

[11] E. H. Holmes, "Procedure Employed in Analyzing Passing Practices of Motor Vehicles," *Public Roads,* Vol. 19, pp. 209-212, 1939.

Description of Study Locations

It is desirable in studies of this kind to begin with the simplest set of conditions possible in order to avoid complications brought about by special situations. It is also desirable to select locations where sufficient traffic passes to make profitable the

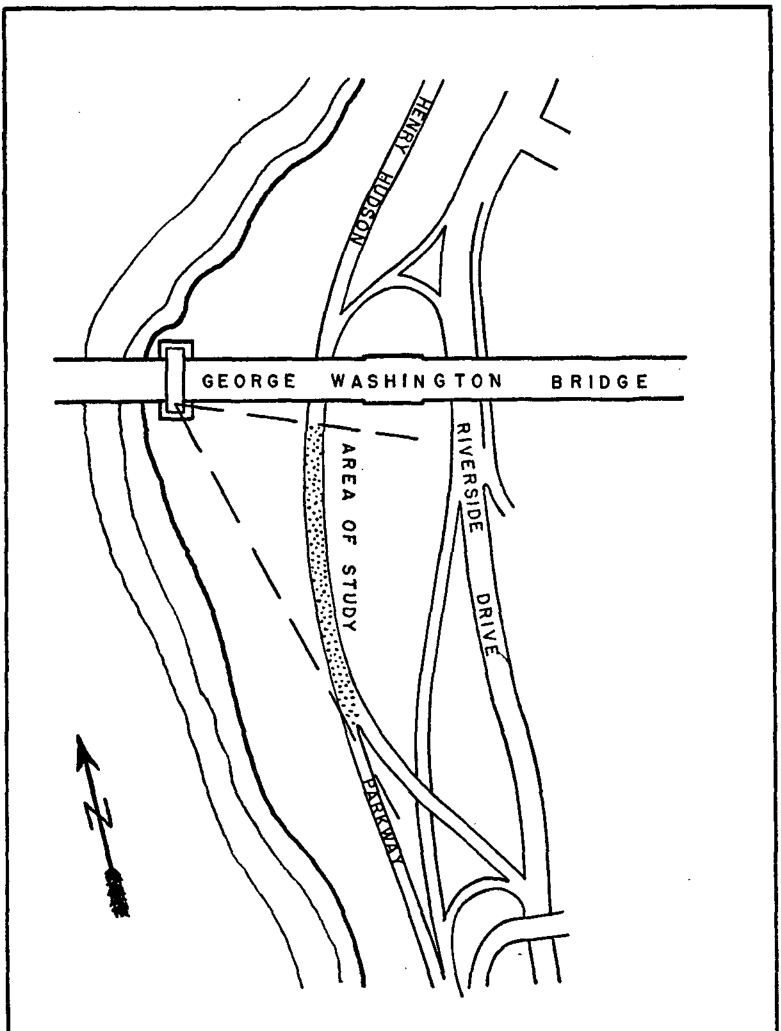

FIGURE 2—Site of Weaving Study on Henry Hudson Parkway near George Washington Bridge.

time spent in study. While the first condition, simplicity, was not too well met, the selected locations were not considered to be too irregular for reasonably accurate analysis.

By using the photographic method as the means of collecting data, a minimum field crew is needed and a very complete record of individual vehicle behavior is obtained. Limitations of the method lie chiefly in the difficulty of finding sites from which to operate the camera. Even with a wide-angle lens, considerable elevation is necessary to get coverage over several hundred feet of roadway. Because of this problem of elevation, locations for study were finally limited to two lengths of road on the Henry Hudson Parkway. A great amount of traffic passes here every day and a considerable amount of weaving takes place. Traffic on the parkway is confined to passenger automobiles, which simplifies the study a great deal.

The first site selected (Figure 2) is located on the southbound roadway of the Henry Hudson Parkway immediately south of the George Washington Bridge. Pictures were taken from the top of the Bridge tower, which provides sufficient elevation for the camera to encompass about six hundred lineal feet of roadway. The pavement here is 44 feet wide and is meant to carry four lanes of traffic. Lane lines have not been marked since paint became scarce during the war, but pavement was laid down in slabs eleven feet wide, so that the construction joints serve to guide the motorist. Most vehicles were observed to operate within lane limits. The posted speed limit is 35 miles per hour.

Traffic from George Washington Bridge merges into that on the Parkway from the left-hand side just north of the bridge. About 1000 feet south of this merging point traffic that is destined for the Bridge or Riverside Drive must leave the parkway, also toward the left. A considerable number of weaves are created by this situation. The area chosen for study lies between the points of merging and diverging traffic.

The second site (Figure 3) is also located on the southbound portion of the Henry Hudson Parkway, opposite Riverside Church at 122nd Street. Pictures were made from the tower of the Church at an elevation comparable to that of the George Washington Bridge tower. However, the horizontal distance between the Parkway and the Church reduced the vertical angle

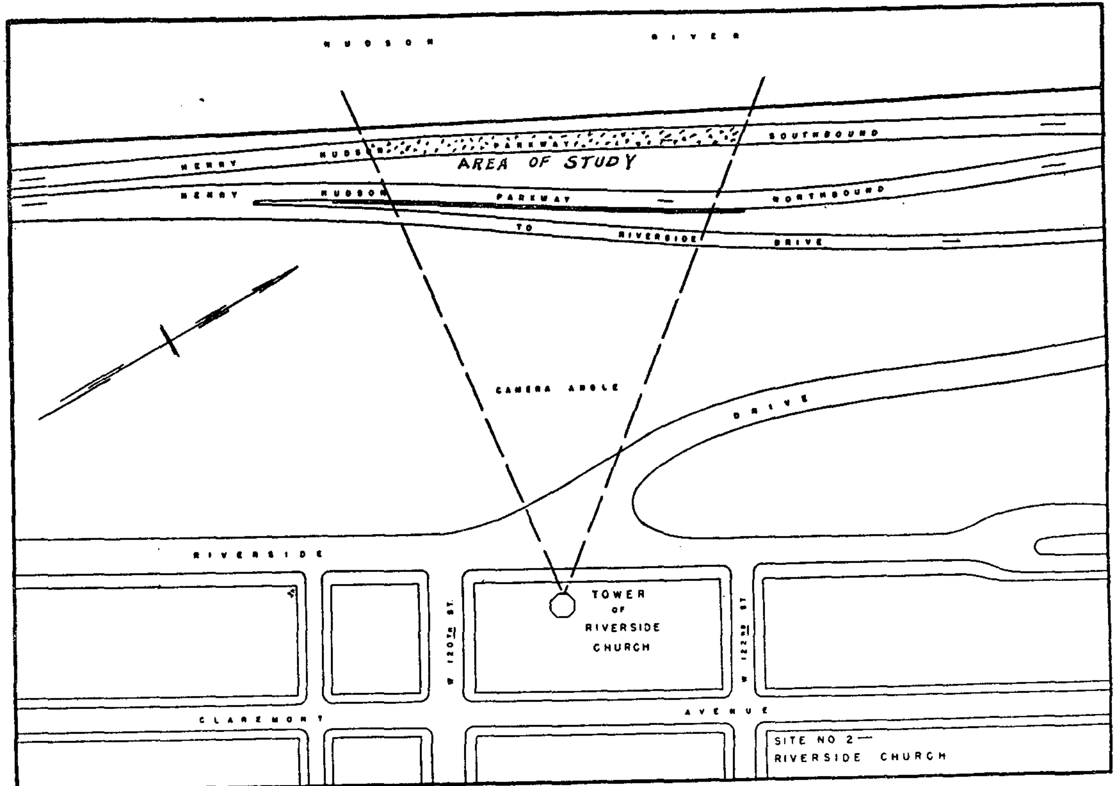

FIGURE 3—Site of Weaving Study on Henry Hudson Parkway Opposite Riverside Church.

of observation to such an extent that lateral movement on the road could not be measured with accuracy.

This section is on a long, 3-lane tangent a few hundred feet south of a merging lane that allows entrance to the Parkway from 125th Street. This merging lane is on the right side of the roadway, and is posted with a stop sign. Weaving movements occur when entering traffic accelerates to the general speed of the Parkway, which usually happens just opposite the camera location.

CHAPTER II

ANALYSIS OF DATA

Definitions

Before taking off data from the films, it was first necessary to subdivide weaves into their basic types and classifications, then to determine the kind and amount of information needed for intelligent analysis of the movements. Following is a listing of weave maneuvers, defined for use in this report: (See Figure 4)

Optional type of weave, wherein the weaving vehicle voluntarily moves from a trailing position behind another moving vehicle into a parallel traffic lane.

Forced type of weave, in which the weaving car is forced into another traffic lane by the presence of a stationary object in the roadway—a parked car in this case.

Both of the above types are further subdivided into four basic classes of weaves:

Free weaves, in which the weaving vehicle is influenced only by the vehicle in the lane directly ahead of it.

Retard weaves, where the weaving vehicle must wait for another car to clear (move ahead) in the parallel lane before the weave maneuver can be commenced. In this instance, the weaving vehicle must frequently slow to the speed of the car directly ahead before the retarding vehicle has cleared sufficiently to permit weaving.

Conflict weaves, in which the weaving vehicle moves into the parallel traffic lane directly in front of another car moving in that lane.

Gap weaves, where the weaving vehicle moves into the restricted space between retarding and conflicting cars. This type is most important in determining the opportunities for weaving under various conditions of speed and traffic volume.

Designation of Vehicles

For convenience in tabulation, the various vehicles involved in weaving movements have been given identifying letters (Figure 4). Thus, *X* is the weaving vehicle; *A* is the vehicle directly ahead of *X*, either moving or stopped; *B* is the conflicting vehicle; and *C* is the retarding vehicle. Other terms employed in this paper:

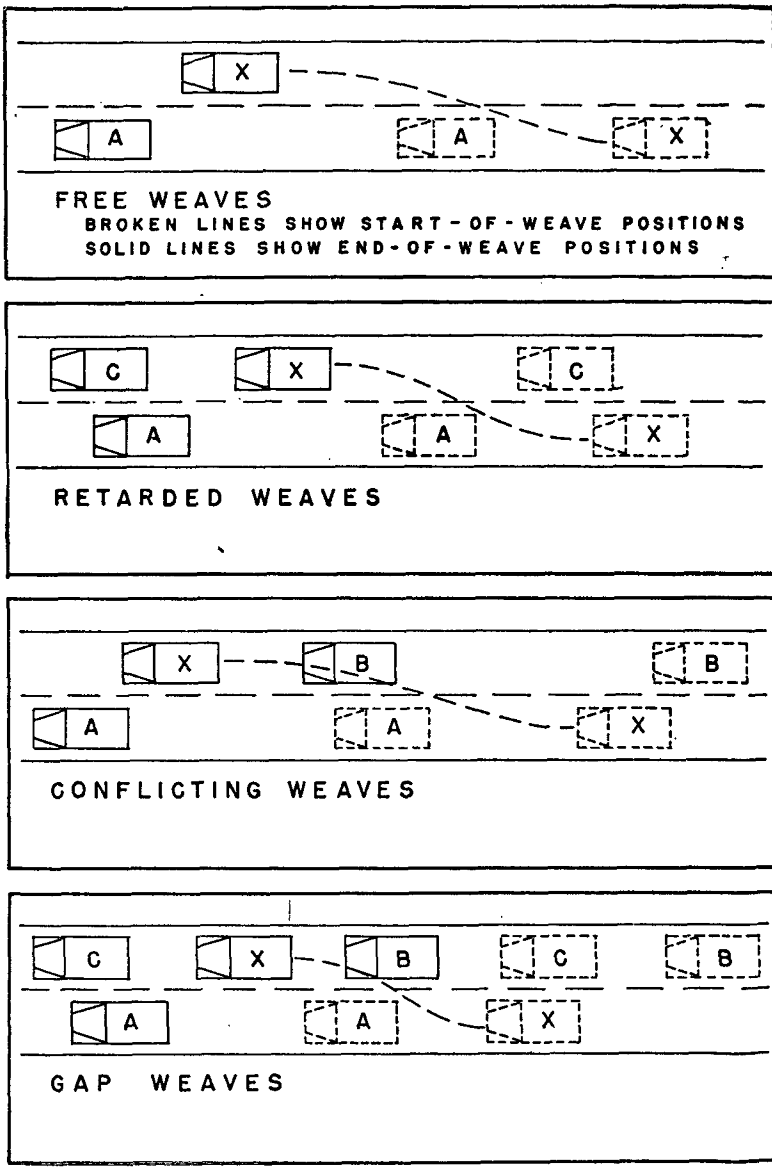

FIGURE 4—Classes of Weaves.

Speed differential—the difference in speed between two vehicles, expressed in miles per hour. Speed differentials when *X* is traveling faster than the other cars are marked +; speed differentials where *X* is the slower-moving car are marked —.

Time is expressed in *frames* of films. Each frame of film is equal to 1/88 of a minute, or approximately 2/3 of a second.

Overtaking time is the time (in frames) that it would take for *X* to close the space between it and *A* at the speed differential existing at the start of weave.

Lateral movement in a weave is the width of weave as determined from placement of the right front wheel in one lane at the start of weave and placement of the same wheel in the adjacent lane at the end of weave.

Length of weave is the forward distance traveled by car *X* while it is moving laterally.

Spacing—the clear distance, in feet, between two vehicles, front bumper to rear bumper.[12]

Time Spacing—the elapsed time, in seconds, between the passage of the rear bumper of one car and the front bumper of the following car.

Method of Tabulating Data

Data from the films were first taken off graphically on coordinate "field sheets". Locations for each car, *X, A, B,* and *C,* were plotted relative to one another for each frame of progress of the vehicle, beginning about two frames before the start of weave and continuing a frame or two past completion of weave. Start and end of weaves were marked for X vehicle. Number of film roll, frame number, type and direction of weave, and width of lateral movement were also recorded on the "field sheets". Sheets were then sorted into groups according to type and class.

After speeds and spacings had been calculated on the field sheets, data were tabulated for use in analysis.[13] From the two

[12] EDITOR'S NOTE: The particular meaning given to spacing should be noted. The other two authors consider the linear spacing and time gap between succeeding vehicles as being measured between corresponding points on the two cars; e.g., front bumper to front bumper. The latter concept is necessary to the application of the theory of probability.

[13] See Appendix I — Tabulation of Wynn's Data.

sets of tabulated data for optional and forced weaves a variety of percentage graphs, bar graphs, and tables were prepared for easy comparison and analysis of findings.

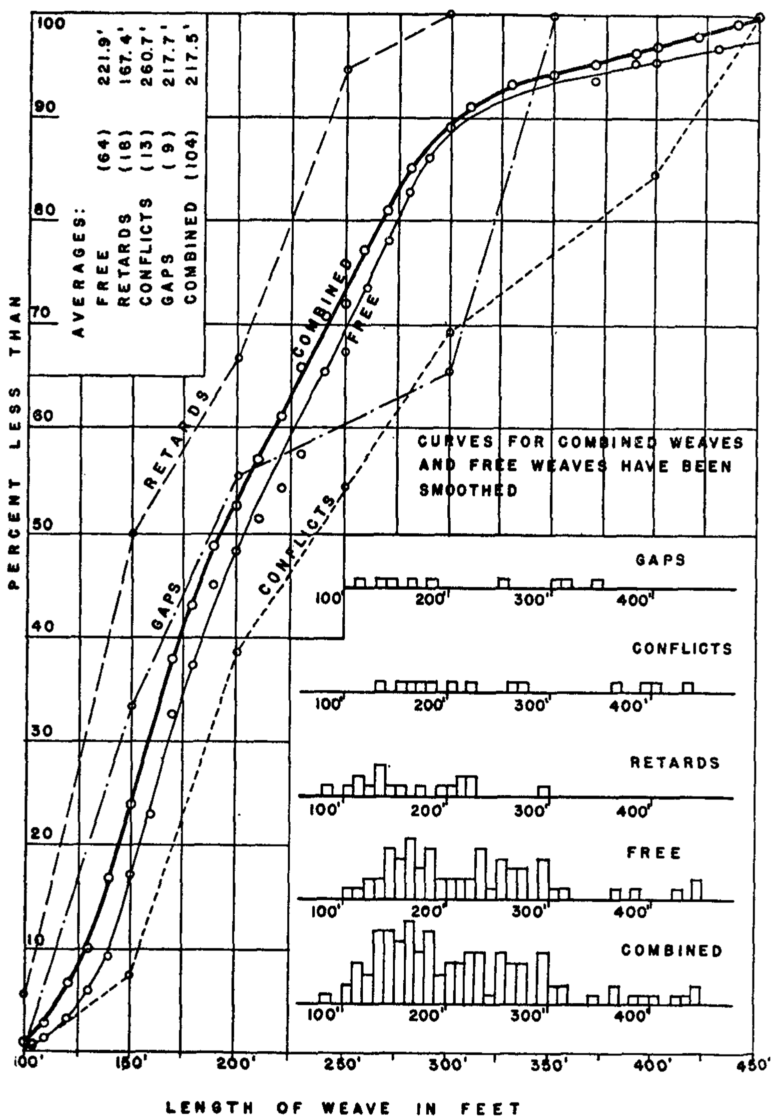

FIGURE 5—Distribution of Lengths of Optional Weaves.

Length of Weaves

The average lengths of all types and classes of weaves are shown in Table I. Weave lengths of optional maneuvers have been grouped by 10-foot increments and shown as a cumulative frequency distribution in Figure 5. Forced maneuvers, because of the small number in each class, were grouped by 30-foot increments, as shown in Figure 6.

TABLE I

AVERAGE LENGTH OF WEAVES

Class of weave	*Optional* No. of Cases	*Optional* Length in feet	*Forced* No. of Cases	*Forced* Length in feet
Free	64	221.9	31	131.9
Retard	18	167.4	25	123.5
Conflict	13	260.7	9	168.6
Gap	9	217.7	24	145.2
Combined	104	217.5	89	136.8

Combined classes of weaves for both types have been plotted as smoothed curves on their respective graphs. Sufficient cases were available for free weaves of the optional type to justify smoothing that curve too. No other curves have been smoothed.

Optional free weaves average about 222 feet in length, and forced free weaves are about 132 feet long on the average. Since these free weaves are made without influence of a third vehicle they probably represent the most desirable values for these conditions.

Optional retarded weaves average about 55 feet shorter than the free weaves, the shorter length being 87 feet. Conflicts are 40 feet longer than free weaves and gap weaves average 5 feet shorter than free weaves, but are so few in number as to lack much significance.

In the forced maneuvers, retards are also the shortest, averaging 123.5 feet. Conflicts are the longest, 35 feet longer than free weaves and 45 feet longer than retards. Gap weaves average almost exactly midway between conflicts and retards.

Retarded weaves, the shortest of both optional and forced types, generally start from a position closer to the passed vehicle than do other weaves. This necessitates a sharper turn to accomplish the maneuver, accounting for the shorter length.

Conflicts, on the other hand, are found to be the longest, possibly because of the motorist's habit of pulling over slowly in front of the conflict car in order to allow the driver of that vehicle sufficient time to react to the new situation and reduce

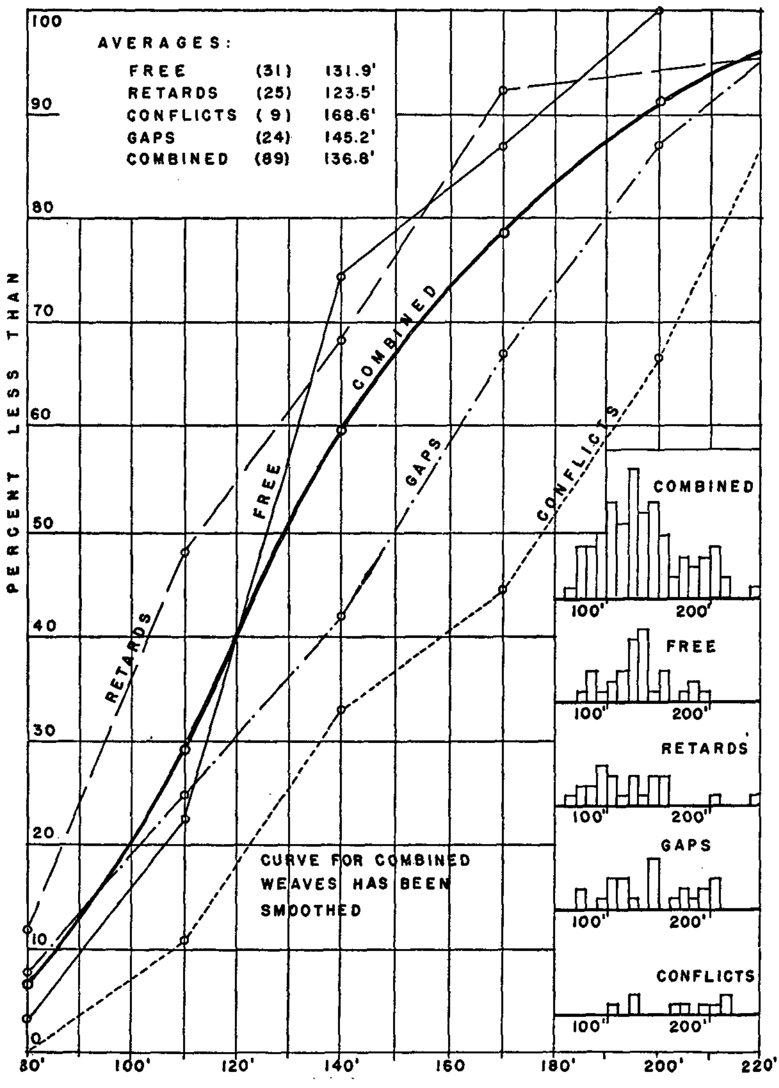

FIGURE 6—Distribution of Length of Forced Weaves.

speed if necessary. This is an example of caution on the part of the weaving driver.

There is probably considerable significance in the reduction in length of weaves of all classes as vehicles moved around a parked car. It is possible that the difference in length of weave occasioned by a stopped vehicle and that made in passing around a vehicle traveling near the general speed of traffic is proportional, directly or otherwise, to the change in speed of the obstructing vehicle. If studies were made of weaving practice around vehicles traveling at a variety of speeds, ranging from stopped vehicles to speeds approaching the average speed of traffic on the highway, the various effects of slow-moving cars on weaving distance could be discovered. The two types of weaves discussed in this paper would seem to be the extreme cases.

Speeds of Weaving Vehicles

Speeds for optional and forced weaves were grouped by 3 mph increments as shown in Figures 7 and 8. Averages for various types and classes are listed in Table II.

TABLE II

AVERAGE SPEEDS OF WEAVING VEHICLES

Class of weave	*Optional*			*Forced*		
	No. of cases	*Speed (mph)*		*No. of cases*	*Speed (mph)*	
		Start	*End*		*Start*	*End*
Free	64	35.8	36.0	31	34.4	32.7
Retard	18	33.3	33.3	25	33.4	31.2
Conflict	13	40.6	41.0	9	39.3	43.7
Gap	9	37.1	37.1	24	34.9	32.1
Combined	104	36.1	36.2	89	34.8	33.2

Average speeds for start of free weaves are observed to be about the same for both optional and forced maneuvers, the optional weave being less than 2 mph faster than the forced weave. Optional weaves were made with almost no change in average speed throughout the maneuver but forced weaves showed a decrease of a little more than 1.5 mph. The range of speeds was greater for forced weaves than for the optional type. Eighty per cent of forced weaves fell within a 15 mile range between 26 and 41 mph, while the same percentage of optional weaves were confined to a 12 mile range between 29 and 41 mph.

Retards occur at slower speeds than free weaves in both

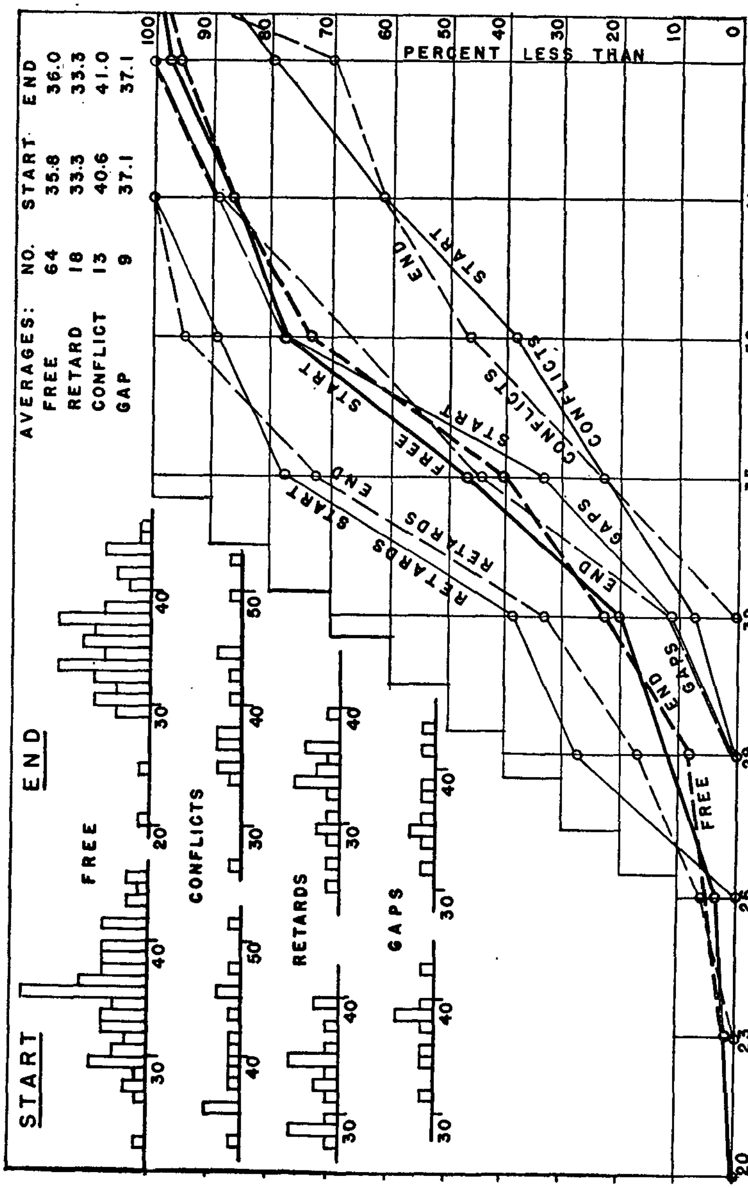

FIGURE 7—Distribution of Speeds of Weaving Vehicles—Optional Weaves.

types of maneuver, the optional type averaging about 2.5 mph slower and the forced type about 1 mph slower. Range of speeds for optional retards are 80% between 26 and 38 mph; and for forced retards are 80% between 26 and 41 mph, ranges

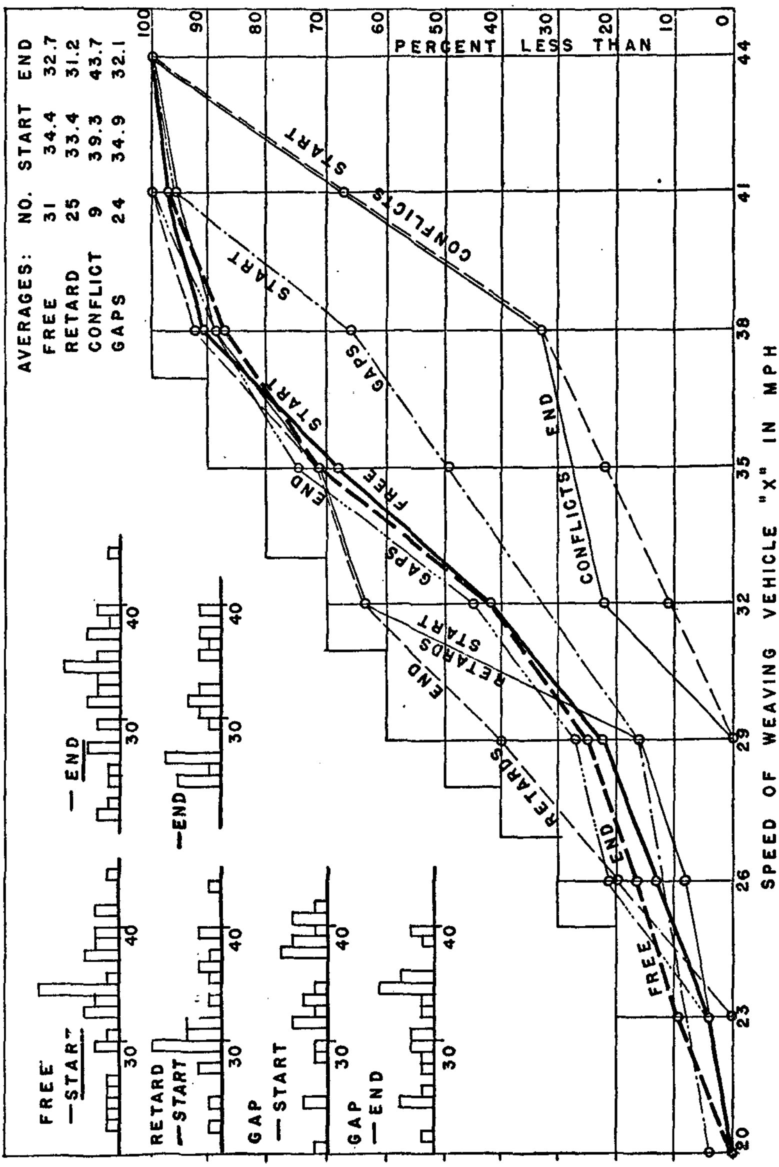

FIGURE 8—Distribution of Speeds of Weaving Vehicles—Forced Weaves.

of the same latitude as those for free weaves. Optional retards showed no change in speed during course of weave but forced retards experienced a little more than 2 mph reduction.

Optional conflict weaves start at an average of 40.6 mph, or 1.3 mph faster than forced conflicts. Both types of conflicts average 5 mph faster than the respective free weaves at the same locations. While optional weaves show a very slight average increase in speed, forced weaves experience a rise of nearly 4.5 mph in differential, emphasizing the "pressure" at the forced situation. About 70% of optional and 80% of forced weaves occur in the 9 mile range between 32 and 41 mph.

Optional gap maneuvers occupy a speed position midway between conflicts and retards but forced gaps are only 1.5 mph faster than retards in that group and about 4.5 mph slower than conflicts. Optional gap weaves show no change in speed during weave while the forced maneuver shows deceleration averaging 2.8 mph. While the optional weaves occupy a narrow 9 mile range between speed values of 32 and 41 mph, the forced weaves are spread over a 15 mile range from 26 to 41 mph. However, it must be noted that only 9 cases of gaps are recorded for optional weaves.

Weaving Time

The time taken for the execution of various classes of weaving movements is shown in Figure 9 for optional weaves and in Figure 10 for forced weaves. Comparative data on averages are shown in Table III. Data for the free movements of both types of weaves are sufficient to permit drawing smoothed curves.

TABLE III

AVERAGE WEAVING TIME

Class of weave	*Optional* No. of cases	*Optional* Time Frames	*Optional* Time Seconds	*Forced* No. of cases	*Forced* Time Frames	*Forced* Time Seconds
Free	64	6.2	4.1	31	4.0	2.7
Retard	18	4.9	3.3	25	3.9	2.6
Conflict	13	6.5	4.3	9	4.3	2.9
Gap	9	5.8	3.9	24	4.4	3.0
Combined	104	5.9	4.0	89	4.3	2.8

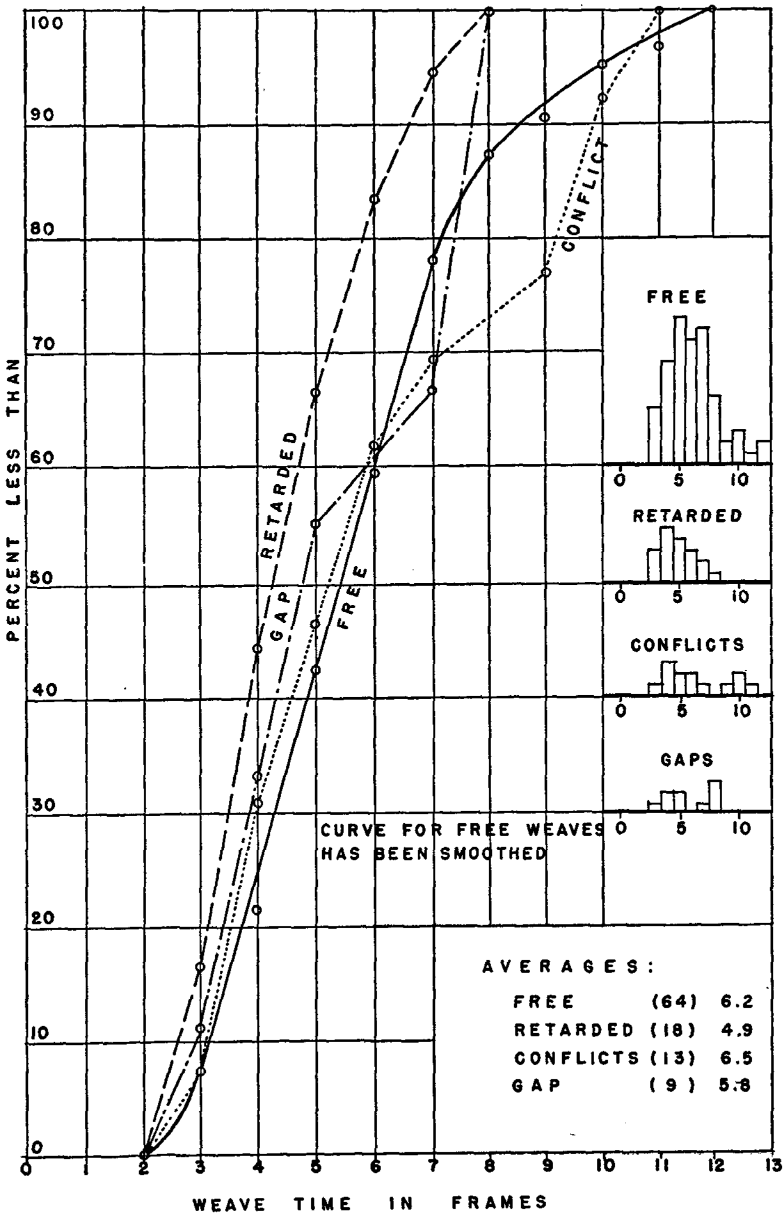

FIGURE 9—Distribution of Weave Time in Frames—Optional Weaves.

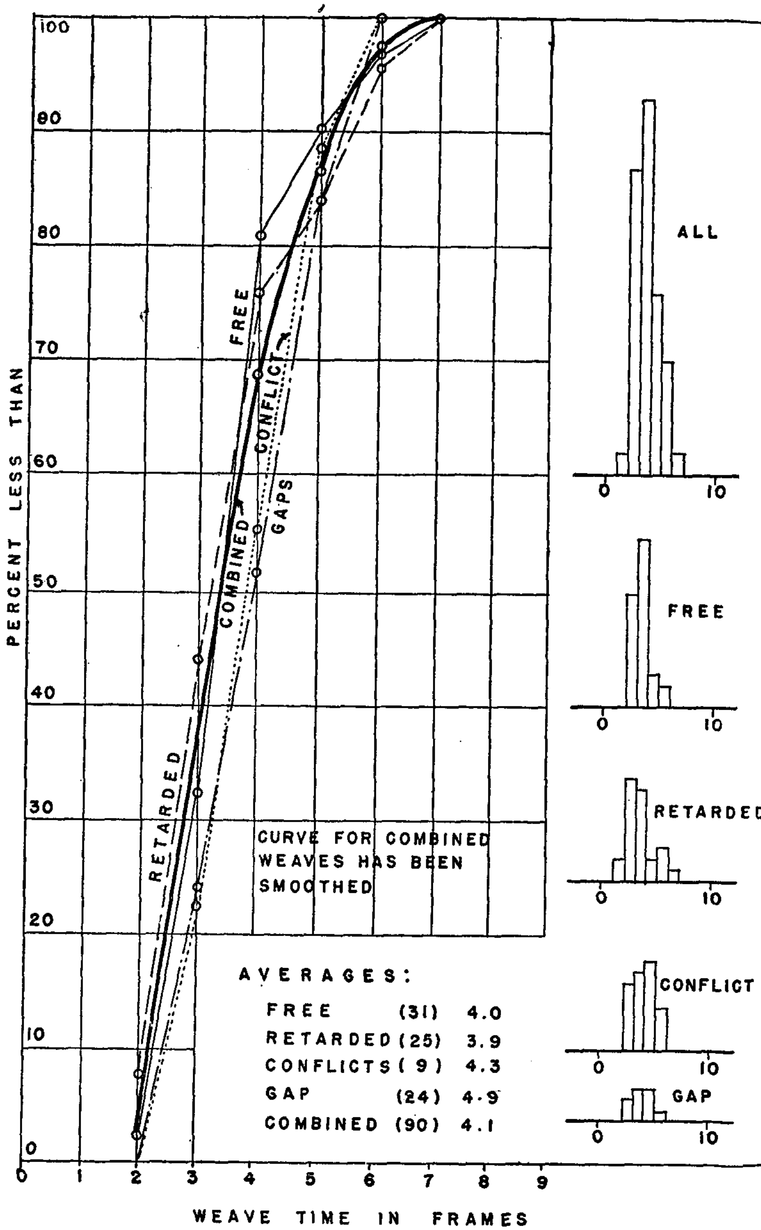

FIGURE 10—Distribution of Weave Time in Frames—Forced Weaves.

Average time for optional free movements is shown to be slightly more than 4 seconds, while forced movements of this class average only 2.7 seconds. This is to be expected, of course, owing to their much shorter length and the fact that start-of-weave speeds are nearly the same for both types. Several maneuvers of the optional type were completed in only 3 frames of time, or about 2 seconds. Quite a number also were observed in this range for the forced weaves.

Retarded movements for optional weaves fell mostly between 3 and 7 frames, or 2 to 4.8 seconds, averaging about 3.3 seconds. The percentage curve conforms to that established for free movements. Forced retards required an average of 0.7 second less than the optional type, almost the same time taken for forced free movements.

Conflicts are longer than the other classes for both types of crossover. Unfortunately, only a few cases are available for study. Optional conflicts extend over a long range, from 3 to 11 frames, while forced conflicts all took place within the 3 to 6 frame range. While optional conflicts average the longest time for all optional classes, 4.3 seconds, forced conflicts rank below gaps, at only 2.9 seconds.

Gap weaves in the forced weave type are sufficient in number to allow a good study. They average 3.0 seconds, highest average for any forced weave, and are distributed evenly over a range of from 2 to 4 seconds. This is not greatly different from the optional type, which range from 2 to 5.3 seconds duration. The average time for both types combined is about 3.3 seconds, which is probably a good *minimum* average for optional type weaves, in view of the fact that about two-thirds of that type range between 2 and 4 seconds duration.

Twenty-five per cent of forced gap weaves take place in about 2 seconds time. This is the shortest time recorded for any of the maneuvers, and is so short an interval that the average driver probably would not use it. However, over 50% of vehicles manage to weave in 2.7 seconds. If we assume a 40 percentile figure, the length of weave would last about 2.5 seconds, which is probably generous enough as minimum time requirement for the forced type of gap weave.

The space-speed pattern established by the optional weaves is again apparent in the relationship of gap weaves to retards and conflicts. The gaps occur at average lengths of time midway between retard and conflict times. There is an interesting relationship here in the fact that the average for equal numbers of retards and conflicts would equal the average time value found for gap weaves, but no particular significance seems to attach to it.[14]

Lateral Movement

It was possible to measure lateral movement with fair accuracy at the George Washington Bridge location so that a trend with regard to width of weave for optional type weaves was discovered. While the distance moved in each case could not be measured closer than the nearest foot, the error should average out for the total of cases studied. These data are shown plotted graphically in Figure 11 and average values are tabulated in Table IV.

TABLE IV

AVERAGE LATERAL MOVEMENT FOR OPTIONAL WEAVES

Class of weave	*No. of cases*	*Width of weave in feet*
Free	64	9.6
Retard	18	8.1
Conflict	13	9.6
Gap	9	9.0
Combined	104	9.2

All weaves were observed to occur within limits of 6 to 15 feet. Two-thirds of retarded weaves occur between 6 feet and 9.6 feet, a range of 3.6 feet; two-thirds of the conflicts fall between 8 and 10 feet, a range of only 2 feet; two-thirds of free weaves fall between 6.6 and 11.5 feet, a range of 4.8 feet, nearly two and one-half times as great a range as the conflicts; and two-thirds of gap weaves occur between 7 and 9.6 feet, a range of 2.6 feet.

Free weaves average 9.6 feet in width and some 37% of them

[14] EDITOR'S NOTE: Further consideration of the correlation between weaving time and the speed of the weaving vehicle might be warranted. For instance, inspection of the data contained in Table XXVI, Appendix I, Gap Forced Weaves, shows an almost constant value of weaving time, regardless of speed. On the other hand the data for Free Optional Weaves, Table XIX, Appendix I, indicate a decrease of weaving time with increased speed.

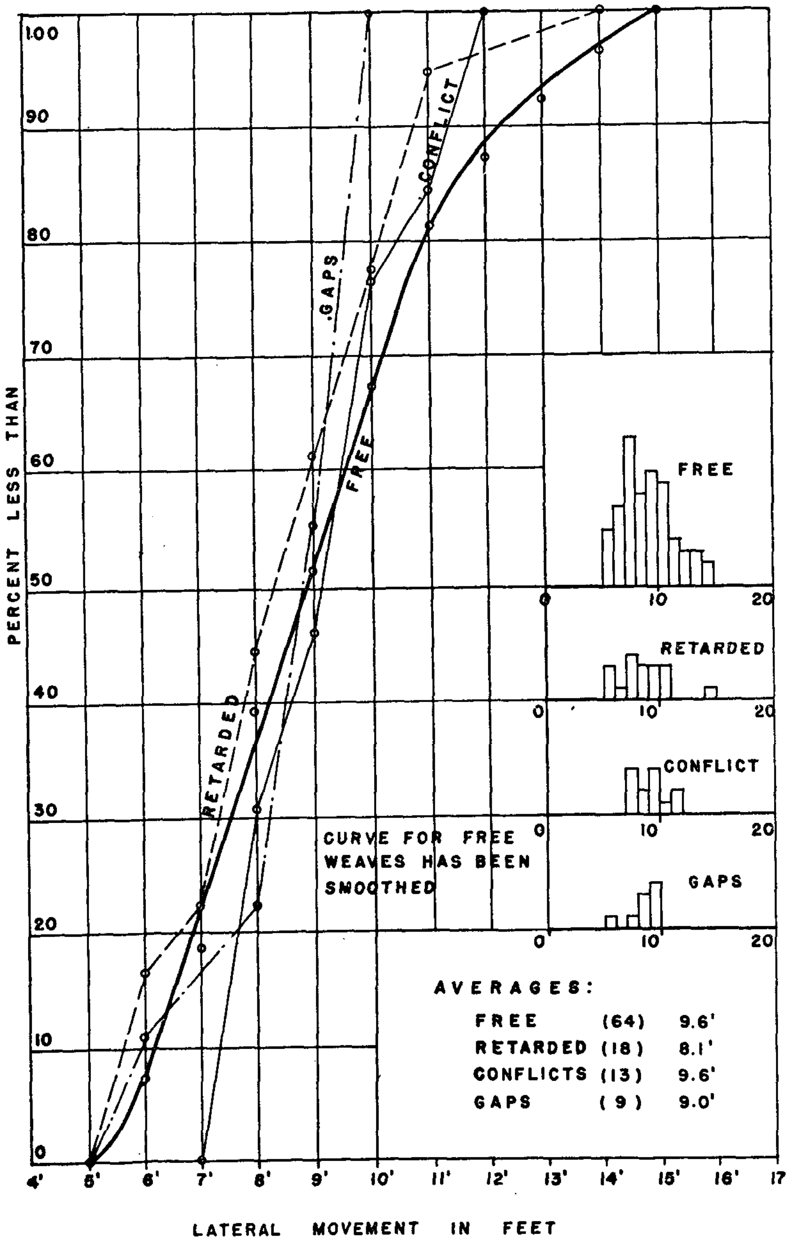

FIGURE 11—Distribution of Lateral Movement—Optional Weaves.

are shown to be less than 8 feet wide. Traffic is usually rather light when free weaves occur, so that the weaving vehicle is frequently not trailing directly behind the overtaken car and the weaving movement, therefore, need not be so wide. On the other hand, the greatest lateral distances are also achieved by the free moving cars, probably because light traffic makes wide-swinging weaves possible, without hazard.

Retarded vehicles make the shortest movements, laterally, of all those measured. This narrowness of weave is probably due to the fact that retarded vehicles are observed to travel as close as possible to the retarding car in anticipation of the weave they are about to make. They are not trailing directly behind the overtaken car at the time of starting the weave but are offset in the direction they plan to weave. While this encroaching practice is technically a part of the weave, the driver may occupy an overlapping position for half a mile or more without changing his lateral position with regard to either lane.

Conflicting weaves have an average width of 9.6 feet, the same as that averaged by free weaves. As observed above, though, conflicting weaves experience the least variation in width, two-thirds of them falling within the 2-foot range between 8 and 10 feet. This is a result of the presence of the conflicting car, which keeps the weaving car in its own lane until sufficient speed differential is reached to afford a weave. The higher speed differential calls for greater clearance space between passing vehicles, makes for wider weaves around the overtaken car. It is probable that the "pressure" under which the conflict maneuver is made is a factor limiting weaves to the distance necessary for safety, and accounting for the low upper limit and narrow range of weaves.

Gap weaves average 9 feet in width, fall into a category intermediate between retards and conflicts, similar to their relationship to these classes when compared to length, speed, and time of maneuver.

Speed Differentials Between Weaving Vehicle and Trailed Vehicle

Speed differentials between weaving vehicle *X* and vehicle *A*, the passed or trailed car, are shown for optional weaves in Table V and Figure 12. No study of this kind could be made for forced weaves where *A* was stationary.

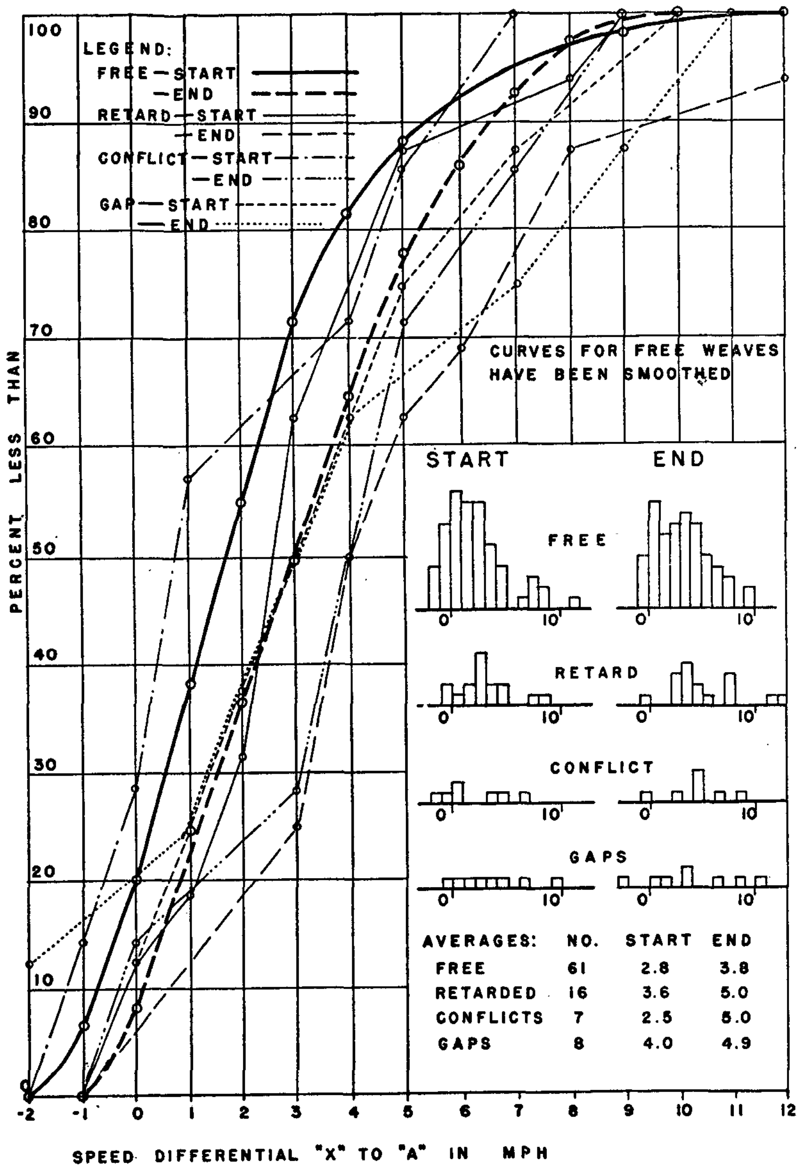

FIGURE 12—Distribution of Speed Differentials Between Weaving and Trailed Vehicles—Optional Weaves.

It will be noted that while a change in speed differential occurred from start to finish of maneuver, practically all the change made is due to a decrease in the speed of vehicle *A*. In each class of weave studied, *A* vehicles are seen to have decelerated by average values varying from 0.8 mph to 1.6 mph, depending upon the class group. The fact that *A* vehicles were reducing speed was probably a contributing cause of weave in some cases.

TABLE V

AVERAGE SPEED DIFFERENTIALS (MPH) BETWEEN WEAVING VEHICLE AND TRAILED VEHICLE

Class of weave	*No. of cases*	*Speed Differential —mph—*		*Speed Change —during maneuver (mph)—*		
		Start	*End*	*X*	*A*	*Total (X over A)*
Free	61	+2.8	+3.8	+0.2	—0.8	+1.0
Retard	16	+3.6	+5.0	0	—1.4	+1.4
Conflict	7	+2.5	+5.0	+0.9	—1.6	+2.5
Gap	8	+4.0	+4.9	0	—0.9	+0.9

The chief significance of the speed differentials studied lies in the interesting range of starting speeds for the various classes of maneuvers. Free-weaving speed differentials are surprisingly low and illustrate how small a speed differential need be to encourage weaving on a one-way roadway.

It is unfortunate that more cases could not have been studied in the classes of retards, conflicts, and gaps, since the small number makes information taken from them quite inconclusive. However, proceeding with the available cases, it may be seen that speed differentials for conflicts are only about 2.5 mph. Since the weaving vehicle has not usually been retarded in this maneuver, its weave speed probably represents the desired travel speed. The amount of differential necessary to encourage the movement is even lower than it is for free weaves.

Retarded weaves show a decidedly higher speed differential than free or conflict weaves, their starting average being 3.6 mph above the speed of vehicle *A*.

Gap weaves, with a 4 mph differential, show the highest average speed differential of any class studied. It should be expected that gap weaves would require the most "pressure" to get started, since that class of maneuver demands the greatest skill and attention of the driver.

Speed Differentials Between Weaving Vehicle and Retarding and Conflicting Vehicles

Speed differentials between the weaving car and the retarding and conflicting cars have been studied for both optional and forced types of conflict, retard, and gap maneuvers. Figures 13

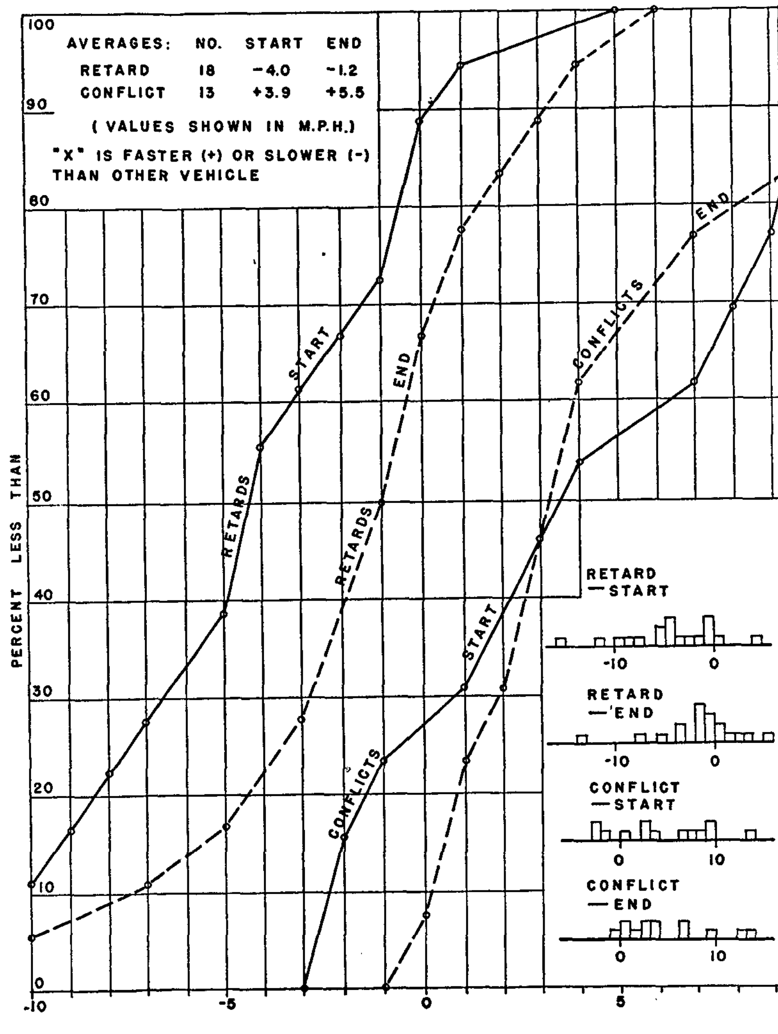

FIGURE 13—Distribution of Speed Differentials Between Weaving and Retarding or Conflicting Vehicles—Optional Weaves.

to 16 show graphic relationships and Table VI gives the average speed differentials for the several classes of data analyzed.

Figures 13 and 14 show the speed differentials for simple retard and conflict maneuvers where only one vehicle in the adjacent lane is exerting an influence on the weaving car.

In the case of optional retard maneuvers, the retard vehicle is shown to be traveling at an average speed some 4 mph faster than the weaving car. This speed differential has been reduced to 1.2 mph by the time the weave is completed, due doubtless to the deceleration of the retarding vehicle, since it was found in the study of speeds of vehicles, above, that the weaving vehicle did not change speed during the maneuver.

With regard to retard weaves in the forced situation, the retarding vehicle was observed to be traveling an average of 2.9 mph faster than weave car at start of weave and 4.4 faster at end of weave. The increase here was due not to an increase in the speed of retarding car, but to decrease in speed of weaving car. Retard weaves, it will be recalled, were the shortest length of all weaves and in the case of forced weaves the driver of the maneuvering vehicle found it necessary or desirable to decelerate while performing his weave in order to avoid striking the parked vehicle or overtaking the retarding car.

TABLE VI

AVERAGE SPEED DIFFERENTIALS BETWEEN WEAVING VEHICLES AND RETARDING OR CONFLICTING VEHICLES

Class of weave	*Vehicle Relationship*	*No. of cases*	*Speed Differential mph*		*No. of cases*	*Speed Differential mph*	
			Start	*End*		*Start*	*End*
Retard	X to C	18	—4.0	—1.2	25	—2.9	—4.4
Conflict	X to B	13	+3.9	+5.5	9	+1.6	+2.5
Gaps—		9			24		
Retard	X to C		—0.7	+0.2		0	—2.5
Conflict	X to B		—0.1	+0.8		—0.4	+0.2

Optional conflict maneuvers began with the weaving vehicle traveling 3.9 mph faster than the conflict car. The difference in speed averaged 5.5 mph at end of weave due to deceleration of conflict car to avoid overtaking the weave car. A different situation is shown for forced weaves. Start of weave with 1.6 mph differential developed to a 2.5 differential by end of weave. In this case the weaving vehicle accelerated to produce the change in speed differentials.

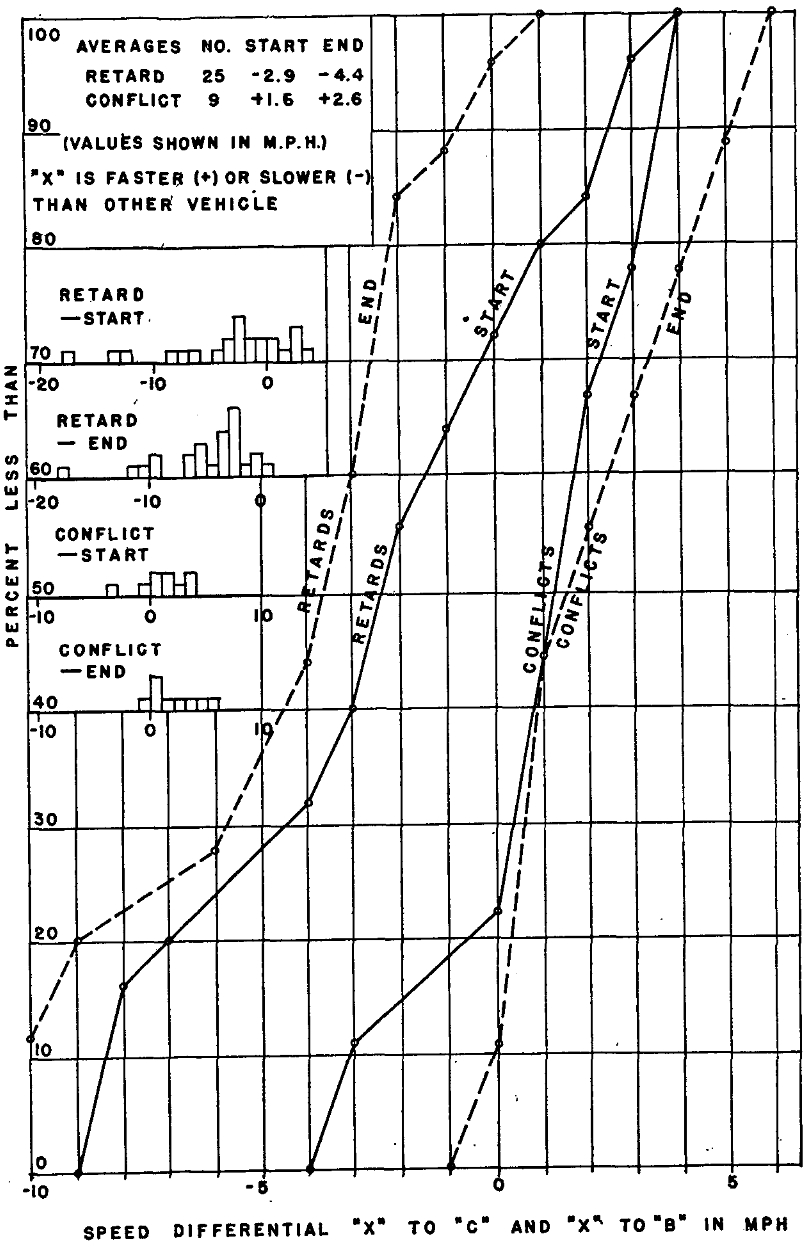

FIGURE 14—Distribution of Speed Differentials Between Weaving and Retarding or Conflicting Vehicles—Forced Weaves.

Figures 15 and 16 show the difference in speed experienced in gap weaves of both types. As will be observed from reference

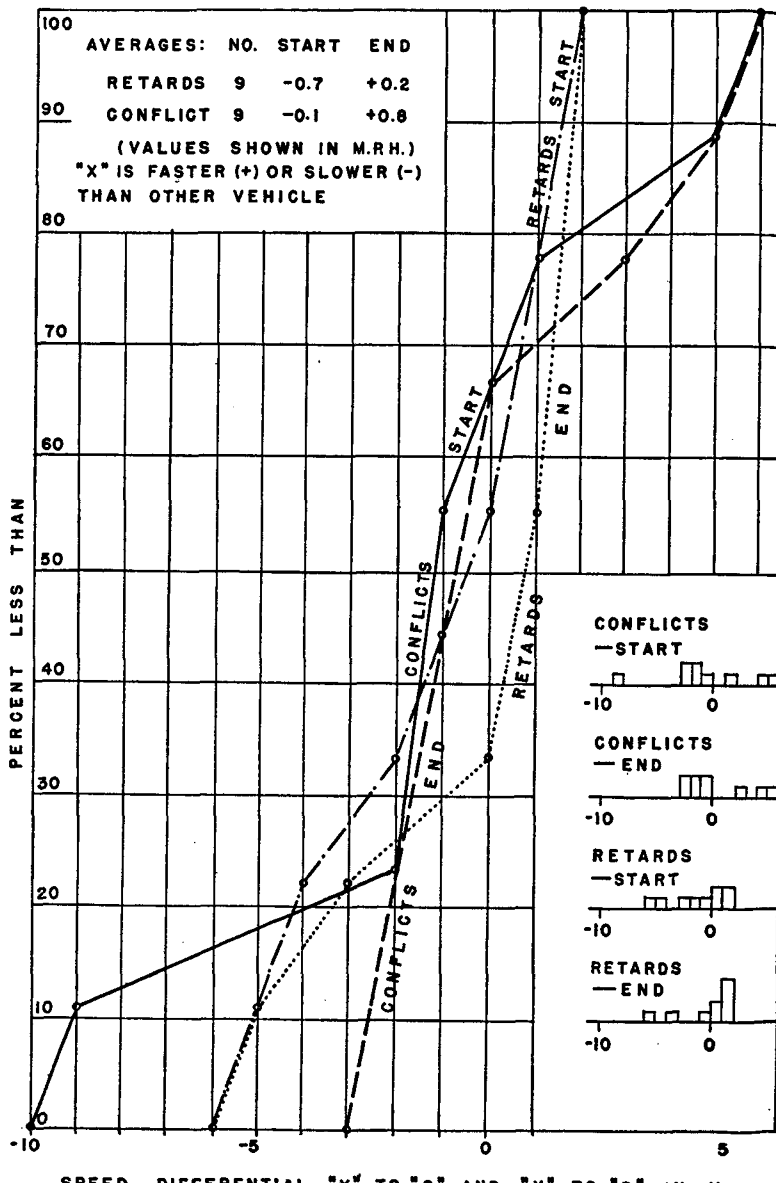

FIGURE 15—Distribution of Speed Differentials Between Weaving and Gap Vehicles—Optional Weaves.

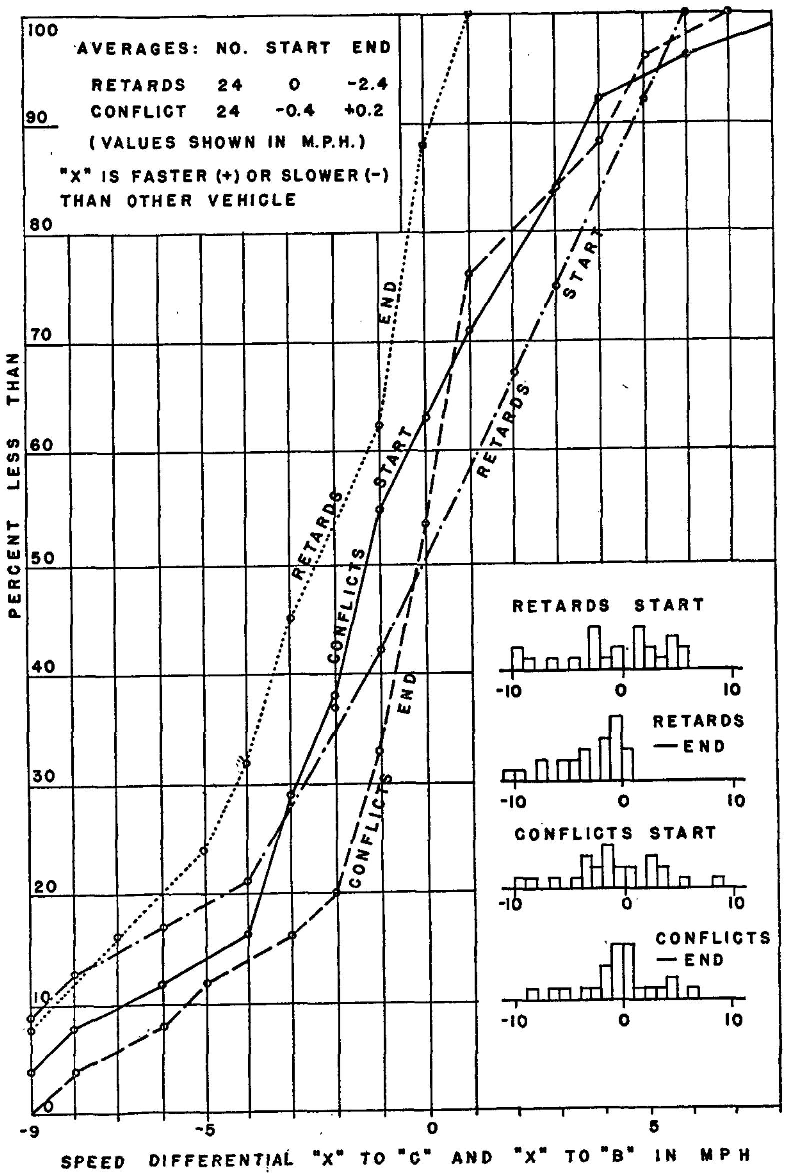

FIGURE 16—Distribution of Speed Differentials Between Weaving and Gap Vehicles—Forced Weaves.

to Table VI, there is very little speed differential between retard vehicle and weaving vehicle in optional weaves. The conflict vehicle is seen to reduce speed an average of about 1 mph. The driver of the weaving vehicle has doubtless approximated the speed of the gap vehicles before executing his maneuver.

It may be seen that much the same thing happens to forced gaps as happens to simple retards and conflicts of the forced variety. Retards commence with both vehicles traveling about the same speed, but the weaving vehicle is forced to reduce speed an average of 2.5 mph during the maneuver. There is even less change in speed differential between the weave car and the conflict vehicle. The weave car commences the maneuver at an average of 0.4 mph slower than conflict car, but forces that vehicle to slow down also, so that conflict car actually must slow down the 2.5 mph differential achieved between the weave car and the retard car, plus an additional 0.6 mph.

Vehicle Spacing

The spacings between the vehicles of various classes are illustrated in Figures 17 to 22 and Tables VII and VIII. With the exception of Figure 18 dealing with distances between weaving vehicles and the stopped car at the start of forced weaves, all graphs concern themselves with the spacing between two moving cars.

Figure 17 shows the spacing from weave car to trailed car by various classes of optional weaves. The total of all weaves

TABLE VII

AVERAGE SPACING BETWEEN WEAVING VEHICLES AND TRAILED VEHICLES (OPTIONAL TYPE) AND AVERAGE DISTANCE BETWEEN WEAVING VEHICLES AND STOPPED VEHICLE (FORCED TYPE) AT START OF WEAVE

	Optional Weave		*Forced Weave*	
Class of weave	*No. of cases*	*Spacing X to A (start of weave) in feet*	*No. of cases*	*Distance X to A (start of weave) in feet*
Free	61	32.1	31	127.5
Retard	17	34.9	25	110.6
Conflict	7	31.3	9	178.1
Gap	8	36.5	24	159.3
Combined	93	34.0	89	135.3

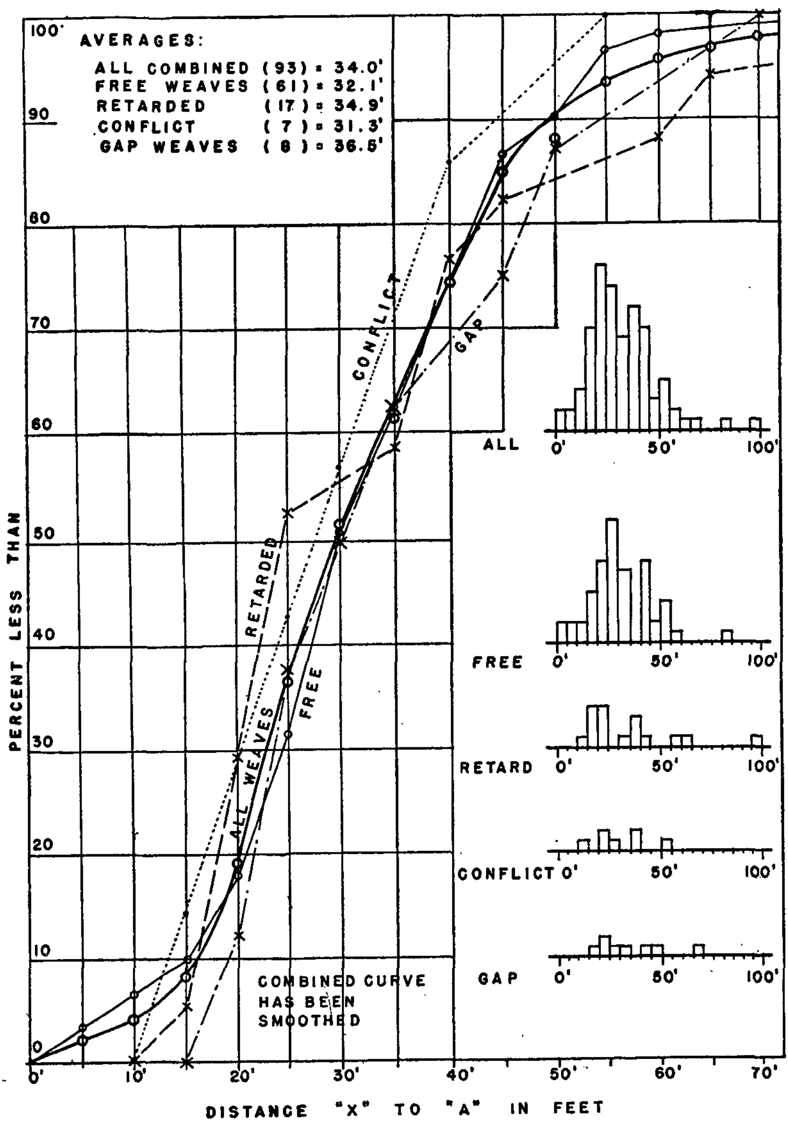

FIGURE 17—Distribution of Spacings Between Weaving and Trailed Vehicles at Start of Optional Weave.

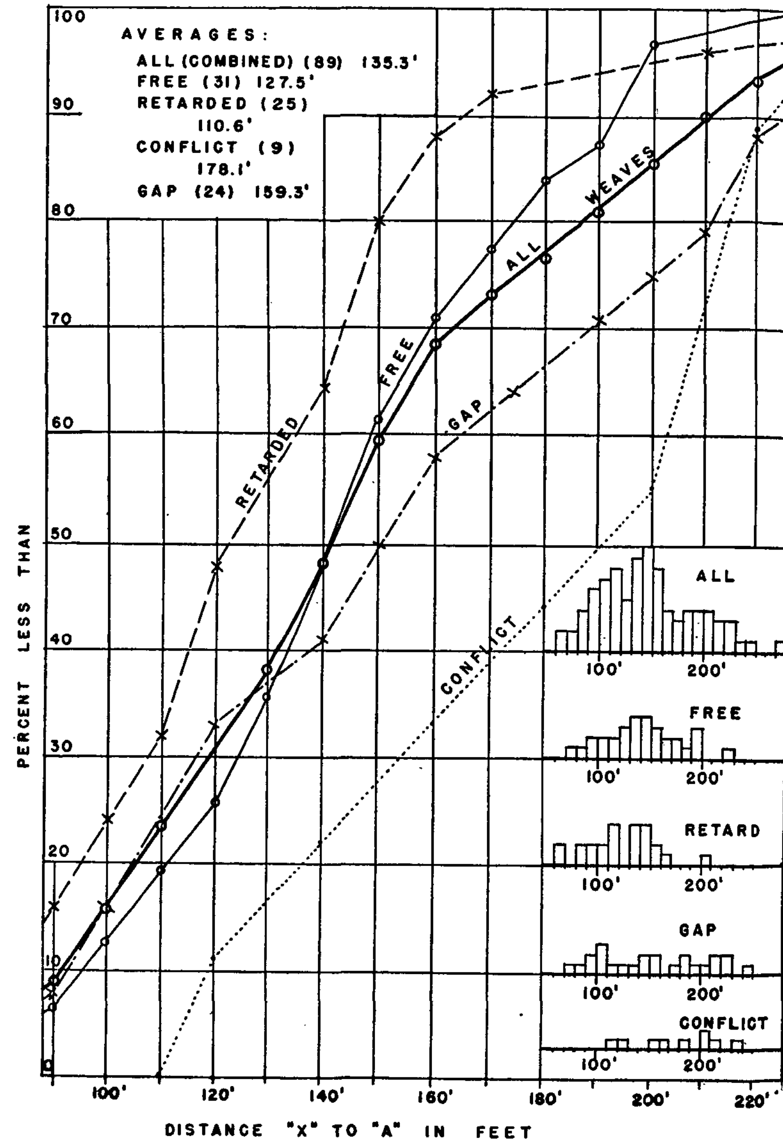

FIGURE 18—Distribution of Spacings Between Weaving Vehicles and Parked Vehicles at Start of Forced Weave.

averages 34.0 feet and ranges from 16 feet for the 10 percentile value to approximately 50 feet for the 90 percentile figure.

Free weaves are shown to begin an average of 32 feet from the trailed vehicle. Retards start 35 feet away, which is rather surprising in view of the fact that in many cases the weaving vehicle has slowed for the maneuver. Conflicts are shorter, average 31.3 feet, and the maneuver actually begins from the closest position, possibly because of their higher speed. Gap weaves start from the greatest distance, an average of 36.5 feet, indicating caution on the part of the drivers entering the most difficult situations.

Figure 18 discloses the various ranges of distance from start of weave to parked vehicle in the several classes of forced weaves. Weave maneuvers are shown to range from less than 80 feet away for about 5% of all vehicles involved, to more than 240 feet for another 5%. Free weaves begin over almost the entire range of distance. The 80 percentile figure is 174 feet.

Retarded weaves are the shortest and they too begin over nearly the whole range of distances, although the 80 percentile

TABLE VIII

AVERAGE SPACING BETWEEN WEAVING VEHICLES AND RETARDING OR CONFLICTING VEHICLES

Class of weave	Vehicle Relationship	Optional Weave: No. of cases	Optional Weave: Spacing in feet Start	Optional Weave: Spacing in feet End	Forced Weave: No. of cases	Forced Weave: Spacing in feet Start	Forced Weave: Spacing in feet End
Retard	X to C	18	14.2	29.0	25	15.5	27.9
Conflict	X to B	13	13.8	42.4	9	12.3	20.8
Gap—		9			24		
Retard	X to C		28.9	30.0		22.4	27.0
Conflict	X to B		35.1	36.7		21.3	21.3

figure is 150 feet, much closer than free weaves. It would be expected that free weaves would be performed at the most desirable distance for the movement, since the vehicles are uninfluenced by other vehicular interference. It is apparent that retarded vehicles were not able to make weaves in so desirable a range.

Conflicts average 178.1 feet from trailed vehicle at start of weave. Gap weaves average about 15 feet farther away than the average free weave.

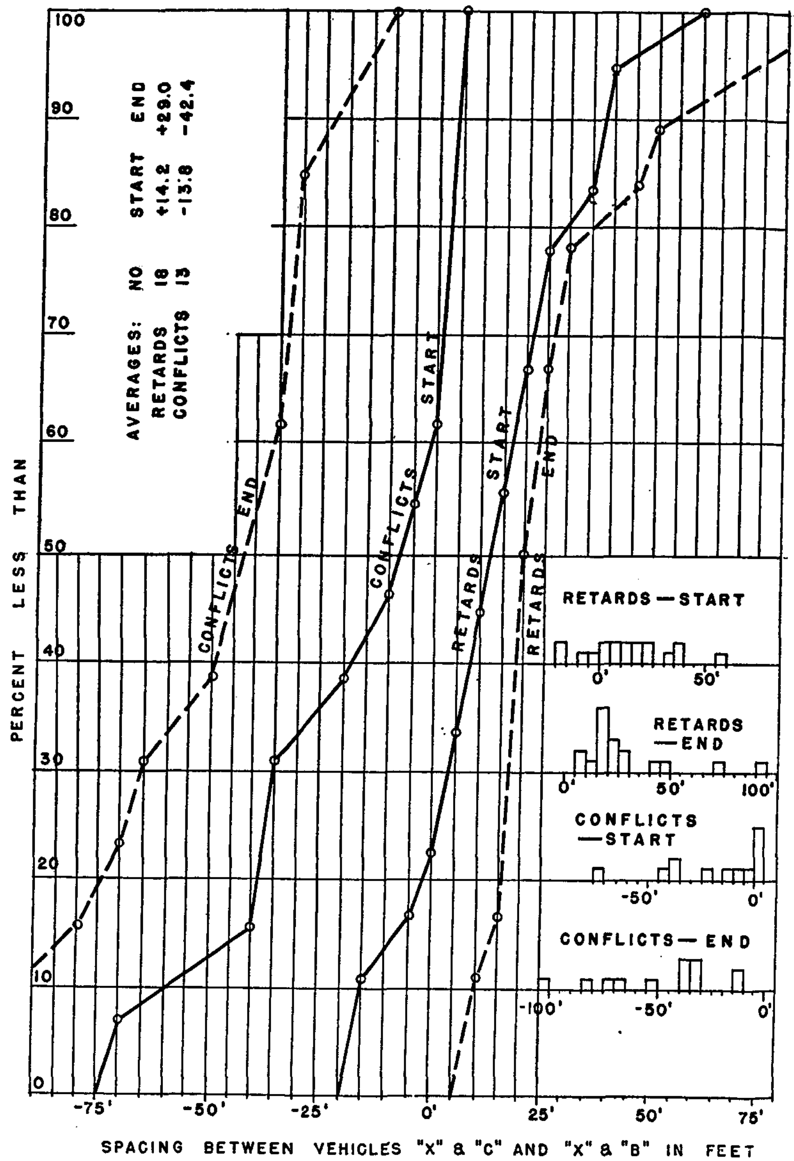

FIGURE 19—Distribution of Spacings Between Weaving and Conflicting and Retarding Vehicles—Optional Weaves.

Figure 19 illustrates the spacing between the optional weave car and retard and conflict cars. The average retard car is 14.2 feet ahead of the weave car at the start of weave. However, some 22% of drivers begin their maneuvers before the retard car has

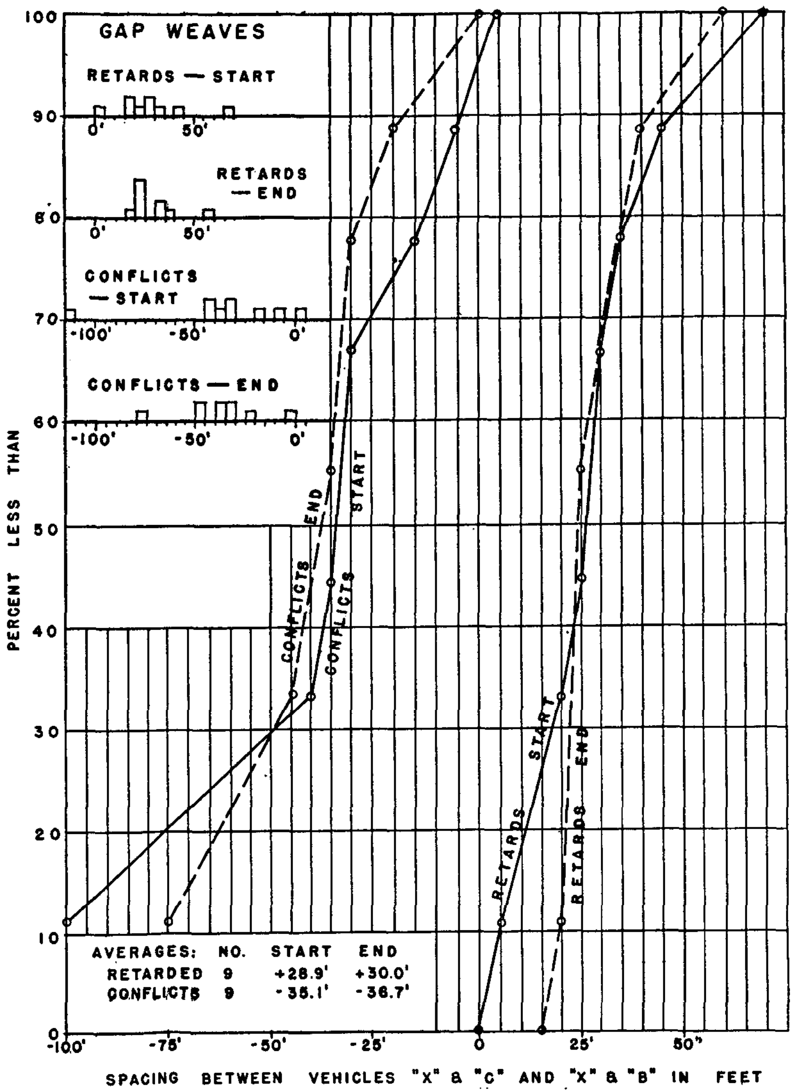

FIGURE 20—Distribution of Spacings Between Weaving and Gap Vehicles—Optional Weaves.

cleared their front bumper, and this at speeds averaging 33 mph for the weaving vehicle and a negative speed differential averaging 4 miles per hour. The average distance apart at the end of weave equals 29 feet, with about 20% of weaving cars only 10 to 15 feet from retard cars at the finish of maneuver.

Conflict cars average only 14 feet from weave car at start of the movement with nearly 40% overlapping it from 1 to 5 feet. However, the weave car is usually traveling about 4 mph faster than the conflict car, which makes this sort of maneuver possible. Conflict cars are an average of 42.4 feet behind weave car by completion of maneuver, less than 20% of them being closer than 30 feet.

Spacing for conflicts and retards of the forced variety are illustrated in Figure 21. The retards are sufficient in number to establish a good pattern, and, fortunately, a similar pattern is established by the few conflicts examined.

Vehicles are shown to begin their weaves an average of 15.5 feet from the rear of the retarding car, although some 44% begin the movement when less than 10 feet away. The average spacing at finish of move is 27.9 feet, with some 28% still spaced as close as 15 feet.

Conflict cars were an average of 12.3 feet behind weave car at beginning of weave with some 20% of them less than 10 feet away. Average distance apart at end of weave was 20.8 feet with 20% still less than 15 feet.

Figure 20 shows the position of optional conflict and weave cars at start and finish of a gap maneuver.[15] It is apparent that there is only a small change in this relationship from start to finish of the weave. The retard car is an average of 28.9 feet away at start of weave and only 1.1 feet further at end of weave. The conflict car is an average of 35.1 feet behind weave car at start of crossover and is but 1.6 feet more distant at the finish. This kind of maneuver is performed by 40% of the weave cars

[15] EDITOR'S NOTE: If two succeeding cars are traveling a mile apart, they obviously do not frame a "gap" in the sense used here. At some maximum spacing, one or the other of the vehicles no longer influences the movement of the weaving vehicle, and the movement becomes a retard weave or a conflict weave. The determination of the maximum distance between succeeding cars which may be considered a "gap" is dependent upon the judgment of the person studying the problem. Mr. Wynn has chosen this maximum value as about 100 feet spacing, or 2.5 seconds of time-spacing.

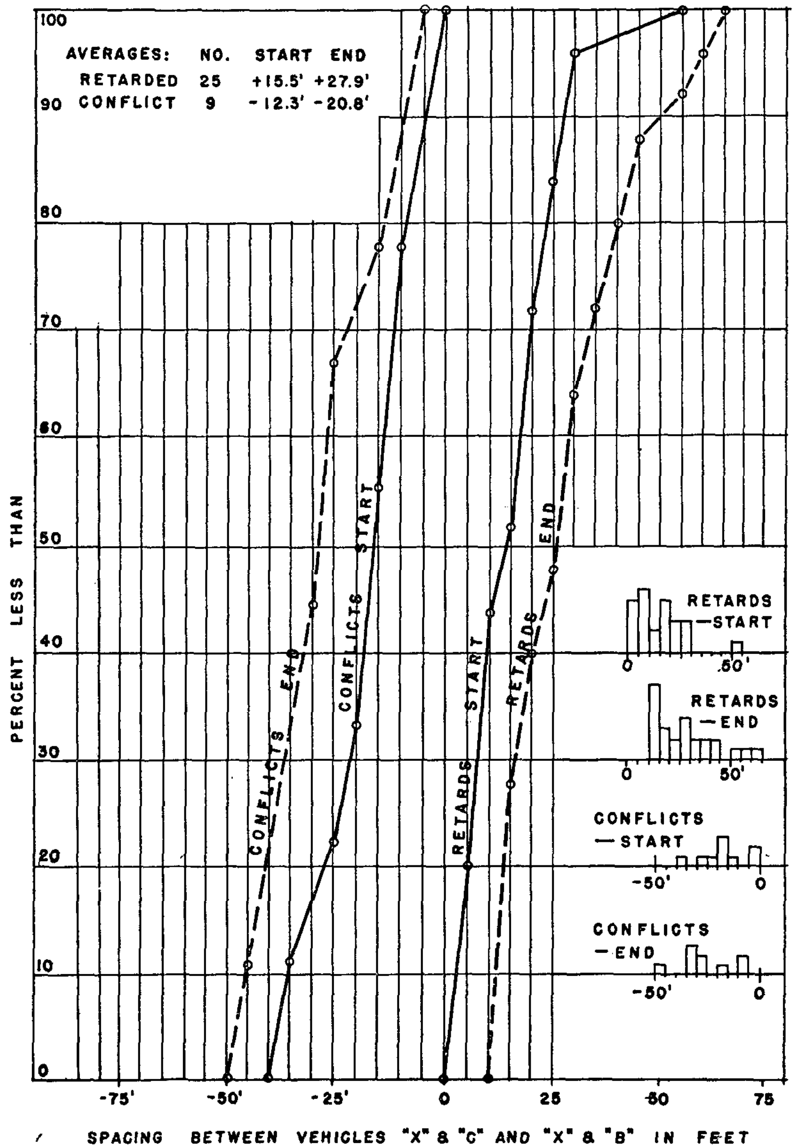

FIGURE 21—Distribution of Spacings Between Weaving and Conflicting and Retarding Vehicles—Forced Weaves.

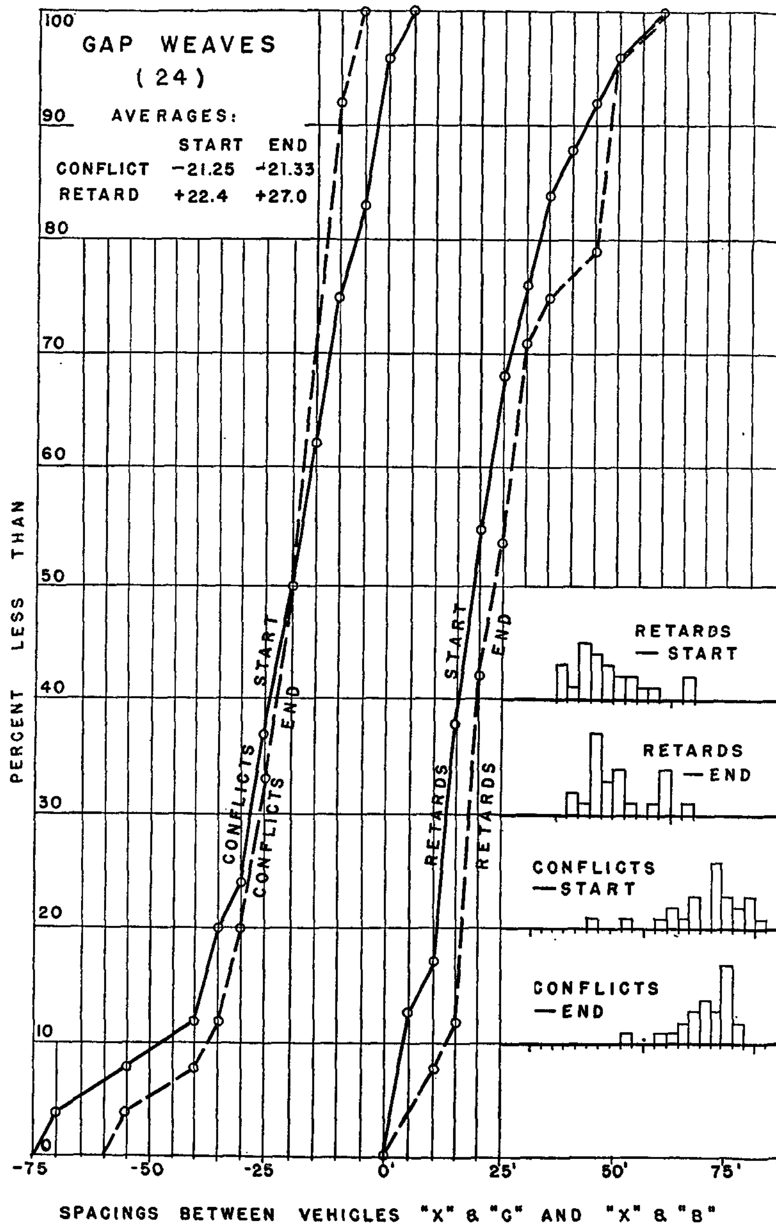

FIGURE 22—Distribution of Spacings Between Weaving and Gap Vehicles—Forced Weaves.

between the 30th and 70th percentiles. It is most interesting to note that longer or shorter than average gaps are usually shortened or lengthened to fit the optimum during the course of the weave, this adjustment being carried out by the conflict car.

It may be noted that the average spacings for simple retards and conflicts at the end of the maneuvers are very close to the average beginning-of-weave spacing for the gap weaves, as can be seen in Table VIII. In fact, distances for retards are almost identical, and the free moving conflict car is only 7.3 feet farther behind weave car than the same class of vehicle is at start of the gap maneuver.

These findings show, then, that the average gap weave is made into a space that is large enough to accommodate the weave without much change in length of space. This is very significant, and the meaning of this will be developed.

Distance divided by speed is equal to the time necessary to travel that distance. Time-spacings of the limiting gap vehicles, *B* and *C*, have been tabulated in Table IX for all optional and forced gap weaves, and are arranged by lengths of time-spacing for each maneuver.[16]

In the case of optional weaves the average time-spacing between *B* and *C* at the beginning of maneuver is 1.6 seconds, reducing to 1.5 seconds by end of weave.

Forced weaves of the gap variety are found to have taken place with time-spacing of *B* and *C* as low as 0.6 second at 39 mph, but with a reduction in speed of the weave vehicle to 35 mph by end of maneuver. This certainly is near the minimum time-spacing that could be accepted.

Average time-spacing accepted in the forced weaves was 1.2 seconds in length, with an average increase to 1.4 seconds length by the end of weave. Average speed of the weaving vehicles for this maneuver was observed to drop from 34.9 mph at start to 32.1 mph at end of weave (see Table II), or a 2.8 mph reduction in average speed.

---

[16] EDITORS NOTE: Mr. Wynn has computed time-spacings by dividing spacing by the speed of the weaving vehicle. The other two authors have computed time values on the speed of the conflicting vehicle. The difference is not large for weaving maneuvers; for merging maneuvers, especially at stop-sign locations, only the latter method is significant.

TABLE IX

Time-Spacing Of Gap Vehicles *B* and *C*, Arranged by Length of Time-Spacings Entered by Weaving Vehicles

Start of Weave			*End of Weave*		
Time-space in sec.	*Length of gap in feet*	*Speed of weave car (mph)*	*Time-space in sec.*	*Length of gap in feet*	*Speed of weave car (mph)*
		OPTIONAL WEAVES			
0.7	43	37	0.7	38	36
1.2	67	38	1.2	73	42
1.3	82	43	1.9	107	43
1.5	75	35	1.4	72	35
1.6	90	39	1.8	102	39
1.6	90	38	1.4	80	38
1.7	78	32	1.8	86	32.5
1.7	83	34	1.8	88	34
2.3	130	38	2.3	116	35
Av. 1.6 sec.			Av. 1.5 sec.		
		FORCED WEAVES			
0.6	36	39	0.7	36	35
0.7	39	38	0.9	46	36
0.7	39	38	1.2	70	39
0.8	38	32	1.0	48	35
0.8	38	33	1.3	54	29
0.9	56	41	1.0	56	36
0.9	55	41	1.4	64	30
1.0	35	25	1.3	53	28
1.0	47	32	1.3	52	26.5
1.0	58	39	1.0	52	36
1.0	52	34	2.0	89	31
1.1	64	35.5	1.3	76	35.5
1.2	64	41	1.1	56	40
1.2	49	29	1.3	48	25
1.3	61	32	1.5	49	22
1.3	74	39	1.5	78	35
1.3	80	43	1.5	88	40
1.4	50	25	1.4	53	25
1.4	78	38	2.0	94	31
1.5	86	40	1.6	83	35
1.5	84	38	1.7	81	33
1.6	52	21	2.1	79	25
2.1	92	30	2.1	91	30
2.7	134	34	2.1	102	34
Av. 1.2 sec.			Av. 1.4 sec.		
Median 1.1 sec.			Median 1.3 sec.		
Mode 1.0 sec.			Mode 1.3 sec.		

The median value for gaps accepted in forced weaves falls between 1.1 and 1.2 seconds, and the modal value is 1.0 seconds (4 cases). The modal vehicles represent a range from the 32 percentile to the 44 percentile values of forced weaves. The cases examined experienced an average increase in length of gap to 1.4 seconds. A definite retarding influence is exerted on the conflict vehicle when weaves take place under these conditions. Speeds of the modal group of weaving vehicles ranged from 25 mph to 39 mph, with an average decrease during weave of 2.3 mph.

Within the limits of the available data, a judgment may be formed as to the minimum time-spacing between limiting gap vehicles *B* and *C* which is acceptable for a weaving vehicle *X* to enter. The absolute minimum gap was found to be 0.6 second, while half the drivers accepted a gap of 1.2 seconds, which entailed a decrease in speed by the conflict vehicle *B*. It appears that a usable minimum time-spacing is 1.4 seconds, since this is the average value attained at the end of forced weaves.

Overtaking Time

Figure 23 and Table X are studies of overtaking time and apply only to optional weaves. Overtaking time at start of weave is the time it would take the weaving vehicles to catch up with the vehicle that is being trailed if both vehicles continue traveling at the speed differential existing at start of weave. Not all vehicles studied were traveling with a positive speed differential. Nine of the 61 free weaves involving the *A* car began at speeds equal to or slower than speed of the overtaken car, so that the chart shows only those cases plotted in which the weaving car was traveling faster than the overtaken car at the start of the weave. In the case of conflicts and gaps, the weaving car was traveling at the same speed as *A* in one case and all the rest were faster. In a few cases in each class, no *A* car was involved. This is especially true for conflict weaves and accounts for the very small number recorded here.

Free weave vehicles would require an average of 17 frames, or about 11 1/3 seconds to overtake the trailed vehicle.

Retards show the shortest overtaking time, an average of only 8.7 frames, due to the fact that quite frequently they have been forced to decelerate to the speed of the overtaken

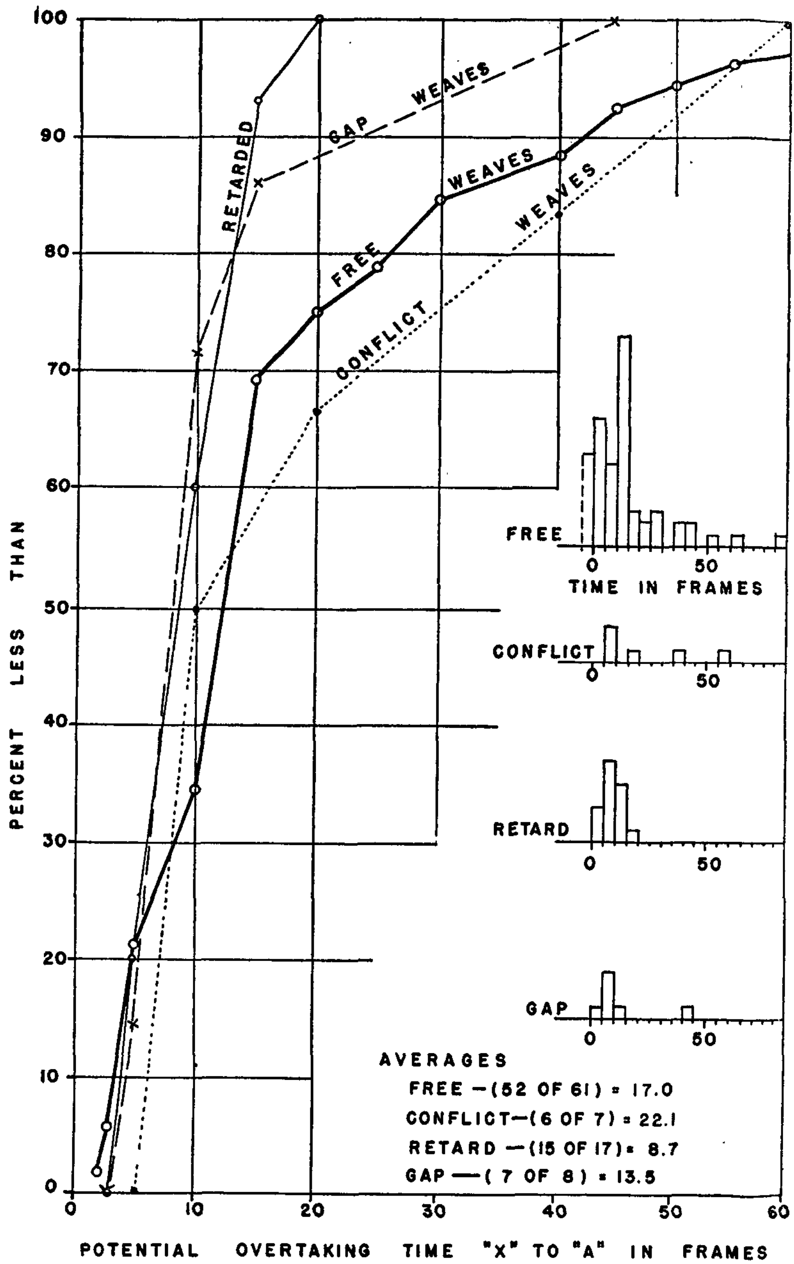

FIGURE 23—Distribution of Potential Overtaking Time at Existing Speed Differential Between Weaving and Trailed Vehicle at Start of Optional Weaves.

car while retarding vehicle clears. Then, before starting the weave, the driver usually accelerates for a short distance so that his speed at start of weave is faster than that of the overtaken car, making for short overtaking time with relation to speed differential and the short distance between vehicles.

Conflicts show the longest overtaking time, an average of 22.1 frames. However, this value is only for six vehicles, and would probably vary considerably if more cases were studied.

TABLE X

AVERAGE OVERTAKING TIME — OPTIONAL WEAVES

Class of weave	*No. of Cases*[17]	*Overtaking Time* *Frames*	*Overtaking Time* *Seconds*
Free	52 of 61	17.0	11.3
Retard	15 of 17	8.7	5.8
Conflict	6 of 7	22.1	14.7
Gap	7 of 8	13.5	9.0

This study of overtaking time is important when one recalls that weaving vehicles, on the average, show practically no change in speed during time of their maneuver, which means that in many cases, as shown by the graph, the *A* car has been overtaken by the time the weave movement is completed. The effective weaving time is limited to the overtaking time, or else the weaving vehicle will be forced to decelerate. This overtaking time is shortened by deceleration of the overtaken vehicle, which was shown to slow an average of 0.8 mph to 1.6 mph, depending on the class of weave.

[17] Cases not analyzed showed no speed differential, or a negative differential.

Chapter III

SUMMARY OF ANALYSIS

Table XI is a summary sheet for the tabulated averages that appeared with each topic as it was discussed, and is placed here for ready reference to other summary material.

In summarizing the data discussed it will only be necessary to refer to the significant findings that stand out as most important for each category of material analyzed:

1. *Lengths of Weave*: *Optional*—Conflicts are the longest class of weave, due to the driver habit of pulling over slowly in front of another car, at the same time traveling at a speed faster than average for the roadway.

Retards are the shortest weaves due to the fact that the weaving vehicle starts from a position closer to the trailed vehicle and must turn out sharply in order to avoid overtaking the trailed car.

Forced—When traffic is forced to pass around a stopped car, the length of weave is considerably reduced, probably because perception of the obstruction does not occur until drivers are quite close to the stopped car.

2. *Speed of Weaving Vehicles*: Average speeds for free weave vehicles are assumed to represent the average speed on the parkway. Optional weaves averaged 35.8 mph at start of weave, about 1.5 mph faster than the forced weaves. Optional weave vehicles experienced little change in speed during the maneuver, but forced weave vehicles were observed to show small decelerations.

3. *Weaving Time*: Gap weaves are discovered to follow a pattern for length, speed, and time which falls midway between the values for conflicts and retards. Gap weaves experience the same sort of restraints that are imposed on conflict and retard weaves, but upon a much smaller scale, being limited to very small changes of speed and distance.

TABLE XI
Tabulation of Average Values

Topic	*Optional Weaves*				*Forced Weaves*			
	Free	*Retard*	*Conflict*	*Gap*	*Free*	*Retard*	*Conflict*	*Gap*
Length of weave in feet	221.9	167.4	260.7	217.7	131.9	123.5	168.6	145.2
Av. Speeds (mph)								
Start	35.8	33.3	40.6	37.1	34.4	33.4	39.3	34.9
End	36.0	33.3	41.0	37.1	32.7	31.2	43.7	32.1
Weaving time—								
Frames	6.2	4.9	6.5	5.8	4.0	3.9	4.3	4.4
Seconds	4.1	3.3	4.3	3.9	2.7	2.6	2.9	3.0
Lateral Mov't. in feet	9.6	8.1	9.6	9.0				
Speed Diff. (mph)								
X—A Start	+2.8	+3.6	+2.5	+4.0				
End	+3.8	+5.0	+5.0	+4.9				
X—C Start		−4.0				−2.9		
End		−1.2				−4.4		
X—B Start			+3.9				+1.6	
End			+5.5				+2.6	
Length of Gaps in feet								
Retard Start				−0.7				0
End				+0.2				−2.5
Conflict Start				−0.1				−0.4
End				+0.8				+0.2
Vehicle Spacing in feet								
X—A	32.1	34.9	31.3	36.5	127.5	110.6	178.1	159.3
X—C Start		14.2				15.5		
End		29.0				27.9		
X—B Start			13.8				12.3	
End			42.4				20.8	
Length of Gaps in feet								
X—C Start				28.9				22.4
End				30.0				27.0
X—B Start				35.1				21.3
End				36.7				21.3
Overtaking Time								
Frames	17.0	8.7	22.1	13.5				
Seconds	11.3	5.8	14.7	9.0				

Time for weaving varies from an average value of 3.3 seconds for retards to a value of 4.3 seconds for conflicts, in optional maneuvers. Forced weaves are executed in much shorter times, their average ranging from 2.6 seconds for retards to 3.0 seconds for gap weaves.

4. *Lateral Movement*: *Optional*—The width of weaves seems to bear some relation to their speed, length, and time of execution. Retards are the narrowest, explained by driver habit of encroaching on desired lane as far as possible before commencing his weave.

Free weaves experience a great range of widths, due to the absence of other traffic on the roadway when they are executed.

Conflicts are the widest weaves, since the presence of conflict vehicle and the high relative speed of weaving vehicle necessary for executing this class of maneuver tends to encourage greater clearance distances between weave vehicle and both conflict and trailed cars.

5. *Speed Differentials*: Variation in speed differentials between optional weave vehicles and trailed vehicles comes about due to deceleration of the trailed car during course of weave. While the differentials in speed between weave and trailed vehicles are not great in any case, it is found that they tend to increase as the maneuver becomes more complicated; thus, gap weaves show the greatest speed differentials of any of the weave maneuvers.

All forced vehicles experience a reduction in speed during the maneuver.

6. *Vehicle Spacing*: *Optional*—Many retarded vehicles are observed to commence their weaves before the retarding car has cleared their bumpers. These weaves took place at average speeds of 33 mph and some 20% of drivers completed their weaves only 10 feet to 15 feet from rear of retard car.

About 40% of conflict weaves were started while the weave car still overlapped the conflict vehicle. Conflict cars were traveling slower by about 4 mph and were an average of 42 feet behind weave car by the end of maneuver.

Forced—Ninety per cent of forced weaves have a spacing between weaving vehicle and trailed vehicle between 80 and 240 feet. Free weaves represent the desirable spacing, 80% occurring between 80 and 174 feet. Retarded weaves occur at the shortest spacing, 80% between 80 and 150 feet. Spacing for conflicts average a little longer than for free weaves, 178.1 feet.

A special study is made of gap weaves of both optional and forced types. It is interesting to note that when a weaving vehicle entered a gap, the speed of the conflicting vehicle was adjusted so that the length of gap at the end of weave was fairly uniform. For the gap weaves measured, the average value of time-spacing was 1.4 seconds.

7. *Overtaking Time*: *Optional*—Retards show the shortest necessary time for the weaving car to overtake the trailed car at speed differentials prevailing between them at the start of weave. Vehicles making conflict weaves, though traveling at higher differentials, are farther away in overtaking time.

CHAPTER IV

APPLICATION OF FINDINGS

The principal significance of the analysis just made lies in the determined values for average time necessary to execute a weaving maneuver, and the average minimum time-spacing that weaving vehicles will accept. Further application, especially with regard to highway capacities, may be possible when more information is available.

Matson and Forbes[18] in their study of passing habits found that the time for maneuvering increased with speed of the passing vehicle. They found values of 8.5 seconds for 30 mph speeds and 9.5 seconds for 50 mph speeds. C. W. Prisk[19] in his studies for the Public Roads Administration verified these findings, although his values for the time necessary for passing are about one second longer than the Matson and Forbes study indicated.

Data used in the present study were insufficient in volume to determine weaving time for other than an average value of speed. However, similarity of weaves to passes will probably permit the assumption that weaves follow the same pattern as passes where time and speed are concerned.

It must be borne in mind that the values for weaving time represent the actual elapsed time from the instant of start to the instant of completion of the maneuver. The values do not take into account the jockeying for position that must frequently occur before the weave can commence. Therefore, these values would represent the minimum time required for merging under ideal conditions.

It should also be emphasized that the values for time of weave are not those required for a vehicle desiring to pass *through* a lane of traffic to a deceleration lane or exit from the roadway. While no studies for such situations were made, it is fair to

---

[18] T. M. Matson and T. W. Forbes; *op. cit.* p. 108.
[19] C. W. Prisk; *op. cit.* p. 370.

state that the required time is undoubtedly longer and would probably approach values equal to twice that shown here. The weave, as considered in this paper, is the act of a vehicle moving from one lane of traffic to about the center of the adjacent lane; weaving from that position to an exit or deceleration lane would be a repetition of this procedure.

From the data available, it appears that 1.4 seconds is the minimum time-spacing between two succeeding vehicles which is acceptable for a gap weave. When traveling at the average speed, 35.5 mph, a car has a time length of 0.35 second. Thus, the minimum time-gap between corresponding points on succeeding vehicles is 1.75 seconds. The frequency of occurrence of time-gaps of 1.75 seconds can be obtained from Figure 1, for volumes of vehicles in a single lane up to 1000 cars per hour.

Use of the chart is best illustrated by an example: At 800 cars per lane per hour the driver of the weave vehicle may start his maneuver at the moment of desire about 70% of the time, so that time-spacings of 1.75 seconds or larger will occur 560 times per hour. In other words, time-spacings of 1.75 seconds or longer occur at the various rates shown for the different volumes of traffic. Per cent of openings, times volume of traffic, indicates at least that number of opportunities to weave will present themselves during one hour of time at any specific point along the lane of traffic. The frequency with which the drivers of weaving vehicles will be able to execute their desired maneuver at the instant they wish to do so is also indicated by the percentage figure. Since no studies were made as to the time-spacing needed for two vehicles to weave simultaneously, the per cent of openings that would allow more than one vehicle to weave cannot be calculated.

In applying both the time-spacing and weave-distance values to traffic situations it must be remembered that the vehicles studied made their maneuvers at speeds approximately equal to those of the retarding and conflicting cars. The values, therefore, are limited to situations where speeds of the vehicles involved are nearly the same, such as occurs on one-way streets, traffic circles, or very long accelerating and merging lanes. Application of data should be made with restraint until further studies have verified their adequacy.

Merging Traffic Characteristics Applied to Acceleration Lane Design

By

STEWART M. GOURLAY

A Thesis

Submitted to

BUREAU OF HIGHWAY TRAFFIC

YALE UNIVERSITY

May 1946

Mr. Gourlay is at present employed as Senior Assistant Traffic Engineer with the City of Detroit Department of Street Railways.

ACKNOWLEDGMENTS

The writer is deeply indebted to Dr. Bruce D. Greenshields and Mr. Donald Schapiro for instruction in the technique of the photographic method which Dr. Greenshields has developed over a period of years, and for interest and encouragement during the progress of the study. Thanks are also due Mr. Theodore M. Matson, Director, and to the other members of the Bureau of Highway Traffic for their many helpful criticisms.

Acknowledgment is made of the friendly cooperation of Mr. Nathan Cherniack and his colleagues of the Port of New York Authority for permission to take photographs from the tower of the George Washington Bridge. Appreciation is also extended to the authorities of the Riverside Church for similar permission.

STEWART M. GOURLAY

Yale University
May 1946

Chapter I

INTRODUCTION

Statement of the Problem

The problem undertaken in this study was the collection of data on merging characteristics of traffic. By comparing driver habits under free conditions with those at places where the merging was controlled by a stop-sign, it was hoped that a new warrant for acceleration lanes would be found. While the data obtained are significant in this respect, a great deal of further research is indicated before all the factors involved can be analyzed. This study should be considered to be a pilot investigation, testing the method and indicating the usefulness of continued research.

Need for Study

The type of research outlined above is particularly timely in view of the large volume of highway construction in the postwar program. A great number of cities have plans for expressway type of development on their arterial routes, and many states are considering limited access construction for relocations of major highways on the new interstate system. In such cases, access to the main roadway will be by merging at a flat angle rather than the conventional type of intersection. Another application of knowledge of merging performance would be in the design of separate right turn lanes at channelized rural intersections.

Although most highway engineers believe acceleration lanes to be desirable, there is considerable difference of opinion concerning their economic justification. If a large enough body of data was available to enable a designer to predict the delays due to merging under different traffic conditions with various types of entrance, it would aid him in deciding which type of entrance design was justified in a particular case. A further refinement might be the prediction of the actual length of acceleration lane needed to minimize ramp delays with a given main roadway traffic volume.

Definitions of Terms Used

Merging. The maneuver in which a vehicle joins a stream of through traffic by slipping into an opening from either side, without having to cross opposing traffic, is called "merging." The most common example is the merging which takes place at the end of an ordinary right turn.

Acceleration lane. An "acceleration lane" is an extra strip of pavement, usually a full lane in width, added along the side of the main roadway lanes at a point of entering traffic. Its function is to assist the merging traffic in finding an opening in the main stream without having to come to a stop. It also protects the through traffic from suddenly finding a slow moving car in its midst.

Ramp. Throughout the following discussion, the term "ramp" will be used to describe any connecting roadway between two intersecting or parallel roadways, one end of which joins in such a way as to produce a merging maneuver. Most ramps connect two intersecting roadways at a grade separation, but the term, as used here, also includes separate right turn lanes at grade intersections, and roadways connecting parallel service drives to the through lanes of express highways or parkways.

Stop-sign location. Any location at which merging traffic is required by regulation to stop before entering the through lanes will be called a "stop-sign location," whether or not an acceleration lane is provided.

Non-stop location. Any location at which merging traffic is able to enter the main roadway without stopping, either due to the presence of an acceleration lane or an unusual balance between main and merging traffic, will be called a "non-stop location."

Time gap. The factor in traffic headway which will be described by the term "time gap" is the interval of time which elapses between the arrival of consecutive vehicles at a given point.

Choice of Sites for This Study

It was desirable to include several hundred feet of road ahead of the merging point in order to measure time gaps, and enough of the road past the start of merging to identify positively the gap accepted. Another primary consideration was the volume of main roadway traffic. It was desirable to have dense enough traffic that merging drivers would be fairly often confronted with the choice of whether or not to accept a small gap. With light traffic, there would be very few actual merging maneuvers.

For comparison, at least two locations were needed, with similar types and volumes of traffic, one stop-sign location, and one non-stop location. Two sites fitting these requirements were found on the Henry Hudson Parkway in New York City.

Description of Sites Chosen

The site chosen for the stop-sign merging study is located on the Henry Hudson Parkway, near 122nd Street, New York City. A ramp leading south from 125th Street joins the southbound side of the parkway at this point, and all ramp traffic is required to stop before entering the parkway. The camera and equipment were placed in the tower of the Riverside Church, on Riverside Drive at 120th Street. From this point, the field of the camera included several hundred feet of the parkway each side of the point where it is joined by the ramp. The elevation above the roadway is enough to enable traffic in different lanes to be distinguished. Figure 24 is a map of the locality, showing the relationship of the ramp, the parkway, and the church.

The non-stop study was made at a point on the Henry Hudson Parkway immediately north of the George Washington Bridge. The south-bound side of the parkway is here four lanes wide, and is joined by a two-lane ramp connecting with Riverside Drive and the bridge. In this case, the camera was mounted on the top of the east tower of the bridge, and a very good view of the roadways was obtained. Figure 25 shows the relationship of the area studied to the camera location.

Limitations of Sites Chosen

The ideal condition for comparing stop-sign and non-stop merging would be to hold all factors constant except the stopping regulation, making before and after studies at the same location. Next to this degree of control, the best situation would be the comparison of two sites at which all the physical factors, such as angle of approach and number of lanes, were similar. The sites studied did not have this ideally rigid control of variables, so

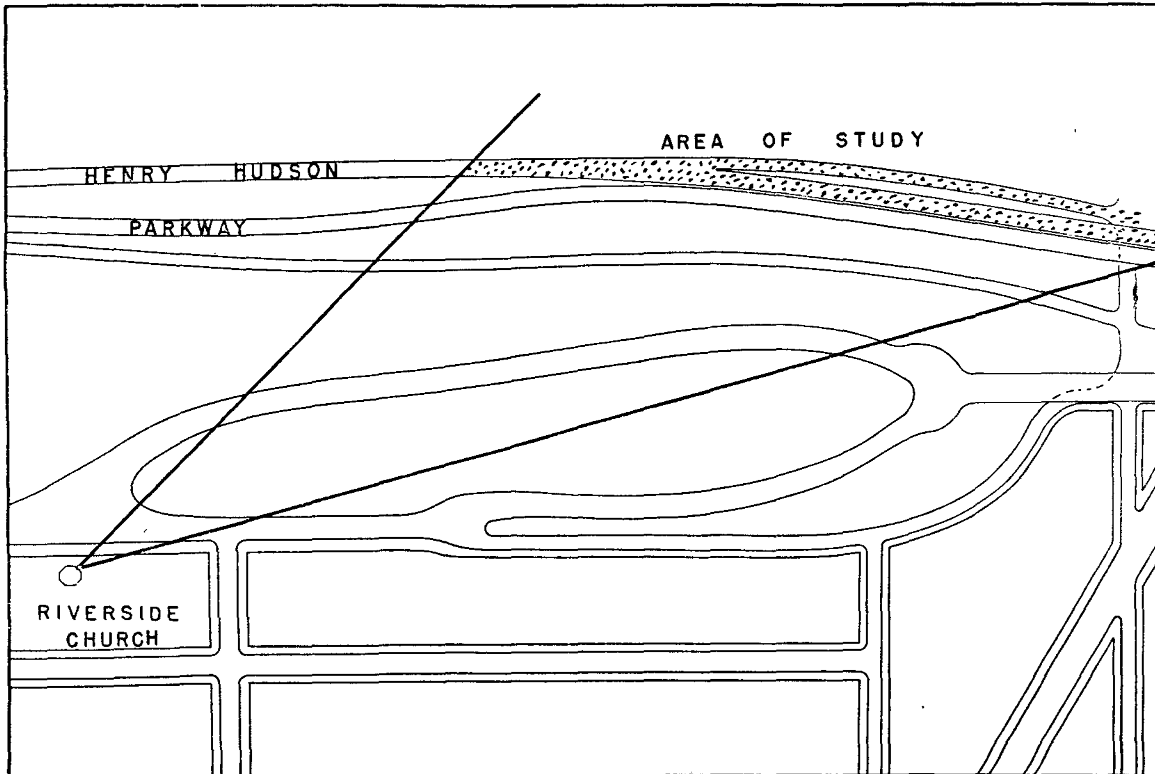

FIGURE 24—Map of Area Included in Stop-Sign Merging Study.

the data are not as reliable as it is hoped they can be made in future studies. As will be seen from Figures 24 and 25, the non-stop ramp enters from the left, at a sharp angle, and at a point where the parkway is four lanes wide; while on the other hand, the stop sign location involves a right entry, a flat angle, and a three-lane main roadway. In spite of these variables, the difference between the data obtained at the two sites is great enough that most of it can be attributed to the stop regulation.

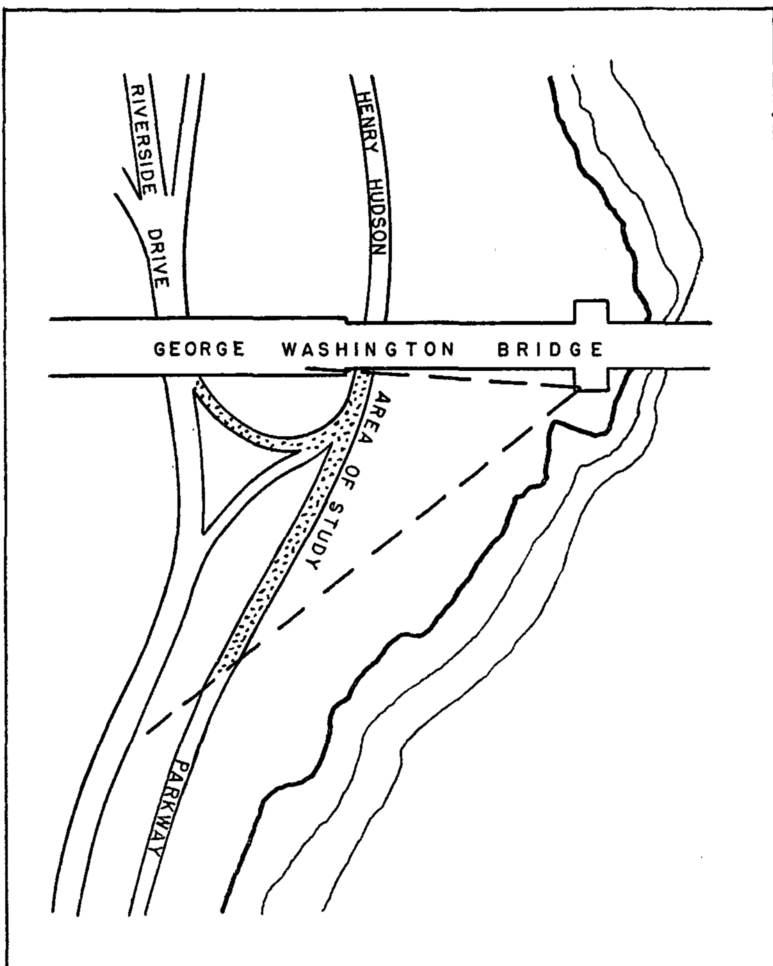

FIGURE 25—Map of Area Included in Non-Stop Merging Study.

Studies Made at Each Site

The photographic studies at both sites were made during the morning peak hour, in order to obtain maximum volume of parkway traffic. The ramp traffic at the bridge was intermittent, being interrupted by a traffic light on Riverside Drive. This made it possible to shut off the camera while there was no traffic entering the parkway, allowing the maximum use to be made of the film. A total of 110 feet of sixteen millimeter film, or approximately 4,400 frames, were exposed at this location.

The beginning of the ramp photographed from the church was hidden from view by a bridge structure, and the cars appeared in a random manner. This made it necessary to run the camera continuously, and in order to include about the same number of merging maneuvers, 200 feet, or 8,000 frames, were exposed.

CHAPTER II

ANALYSIS OF DATA

Choice of Data

The films were run through the projector until a case was found where a driver, wanting to enter the main roadway, was forced to choose an opening between two cars. The locations of the two cars on the marked roadway were then recorded for several successive frames. The difference between the readings for the two cars gave the distance, and the difference between successive readings for the same car was equal to its speed in miles per hour. From these figures, the time gap in seconds was calculated. At the non-stop location, the speed of the merging vehicle was also determined in a similar manner.

The only cases recorded were those in which the entering vehicle was in a position relative to the opening in the main traffic such that the driver was able to choose whether or not he would enter the gap. The procedure was to record the time gap data in all such cases, marking them "accept" or "reject" according to the driver's decision.

Merging Characteristics at Stop-Sign Location

The method of analyzing the films, described above, yielded fifty-four observations at the stop-sign location. The data, consisting of several successive readings of vehicle positions for each maneuver, were first converted into time gap data and tabulated, as shown in Table XXVII (Appendix II). The range of time gaps accepted was found to be 3.4 to 9.7 seconds while those rejected varied from 1.9 to 7.0 seconds. Theoretically, with enough observations, the gaps accepted should have a definite lower limit, but no upper limit, while the rejected gaps should vary from zero to some upper limit.

As the one-tenth second increments were too small to form a satisfactory frequency distribution, the observations were grouped about the whole numbers and arranged as in Table XII. This table is read as follows: of the five drivers facing a two second gap, all rejected it; of the nine drivers facing a three second gap, only one accepted; of the six facing a four second gap, half accepted and half rejected. Figure 26 is a graphic representation of the data of Table XII.

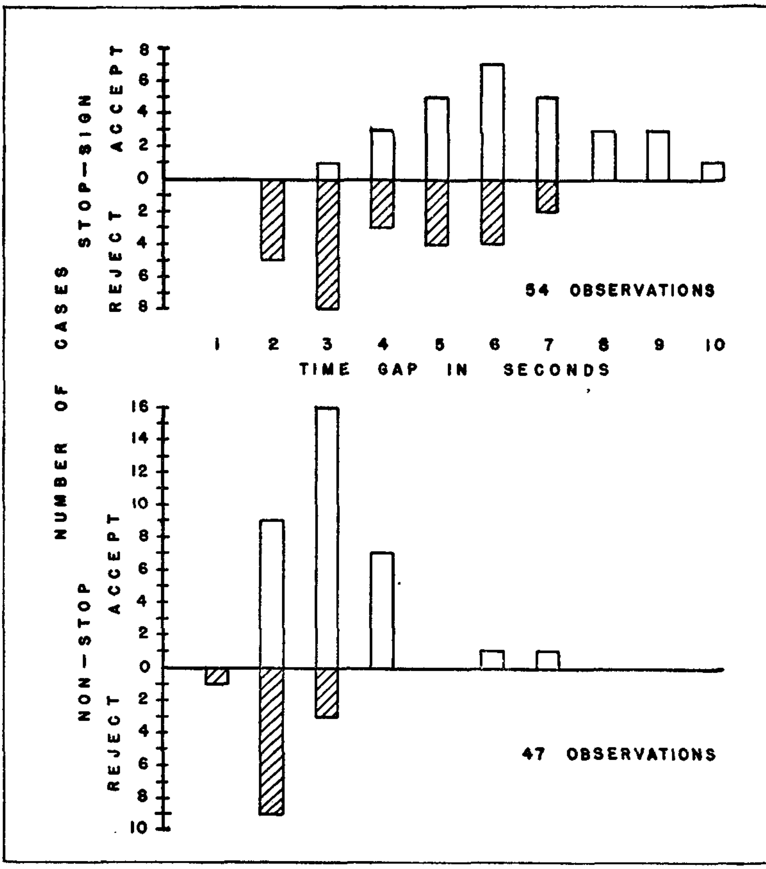

FIGURE 26—Comparison of Accepted and Rejected Time Gaps in Stop-Sign and Non-Stop Merging.

The size of gap accepted by more than fifty per cent of the drivers facing that gap is assumed to be the significant point in determining the practical operation of ramps in a later chapter. It will also be used for comparing the different types of merging. At this stop-sign location, a five second gap was accepted by fifty-six per cent of the drivers. Since this is only a margin of five to four, it is considered more conservative to use the six second gap as the standard for stop-sign merging. Sixty-four per cent of the drivers facing a six second gap will accept it.

It may be of interest to compare this stop-sign merging charac-

TABLE XII

TABULATION OF TIME GAPS IN STOP-SIGN AND NON-STOP MERGING

Time Gap (Seconds)	*Range of Observations (Seconds)*	STOP-SIGN LOCATION				NON-STOP LOCATION			
		Drivers Accepting	*Drivers Rejecting*	*Total*	*Per Cent Accepting*	*Drivers Accepting*	*Drivers Rejecting*	*Total*	*Per Cent Accepting*
1	0–1.4	0	0	0	—	0	1	1	0
2	1.5–2.4	0	5	5	0	9	9	18	50
3	2.5–3.4	1	8	9	11	16	3	19	84
4	3.5–4.4	3	3	6	50	7	0	7	100
5	4.5–5.4	5	4	9	56	0	0	0	—
6	5.5–6.4	7	4	11	64	1	0	1	100
7	6.5–7.4	5	2	7	71	1	0	1	100
8	7.5–8.4	3	0	3	100				
9	8.5–9.4	3	0	3	100				
10	9.5–10.4	1	0	1	100				
				54				47	

teristic with that observed by Greenshields.[20] As part of a study of the urban intersection problem a determination was made of the gap in through-street traffic required by a vehicle waiting to cross a stop-regulated intersection. It was found that, of the vehicles faced with a six second gap, more than fifty per cent would utilize it to make the crossing.

Merging Characteristics at Non-Stop Location

Table XXIII (Appendix II) is the summary sheet for the data obtained at the non-stop location. In this case, the range of time gaps accepted was between 1.5 and 6.6 seconds, while the observed gaps rejected varied from 1.2 to 3.4 seconds. These observations were also grouped about the whole number gaps, and arranged in a frequency table to form the right-hand half of Table XII. The lower half of Figure 26 is a graphical representation of the data.

Although nearly as many observations were obtained at this location as at the stop-sign location (47 instead of 54), it will be seen that the rejections were decidedly in the minority in this case. This was probably because there was nearly the same distribution of gaps in the main traffic, and more of the smaller ones were accepted. Half of the two second gaps presented were accepted, and eighty-four per cent of the three second gaps were accepted. Hence, a gap of three seconds may be used as the characteristic for non-stop merging.

Analysis of Non-Stop Merging by Lanes

The ramp at which the non-stop merging study was made is two lanes wide, and both lanes are utilized a large part of the time. This is due to the accumulation of vehicles at a traffic signal on Riverside Drive before they enter the ramp. The merging observations made at this location were classified by lanes, "lane one" being the lane from which vehicles emerged close to the edge of the parkway, and "lane two" the lane which projected its vehicles into the second parkway lane. The only observations marked "lane two" were those in which two vehicles entered abreast, forcing the outer car to choose an opening in the second lane of the main roadway.

---

[20] Bruce D. Greenshields, *et al., op. cit.,* p. 67.

Under these conditions, it would seem logical to expect the driver in "lane two" to accept a smaller time gap than the driver in "lane one." He is not only under greater urgency because of his exposed position, but is probably a more aggressive driver as

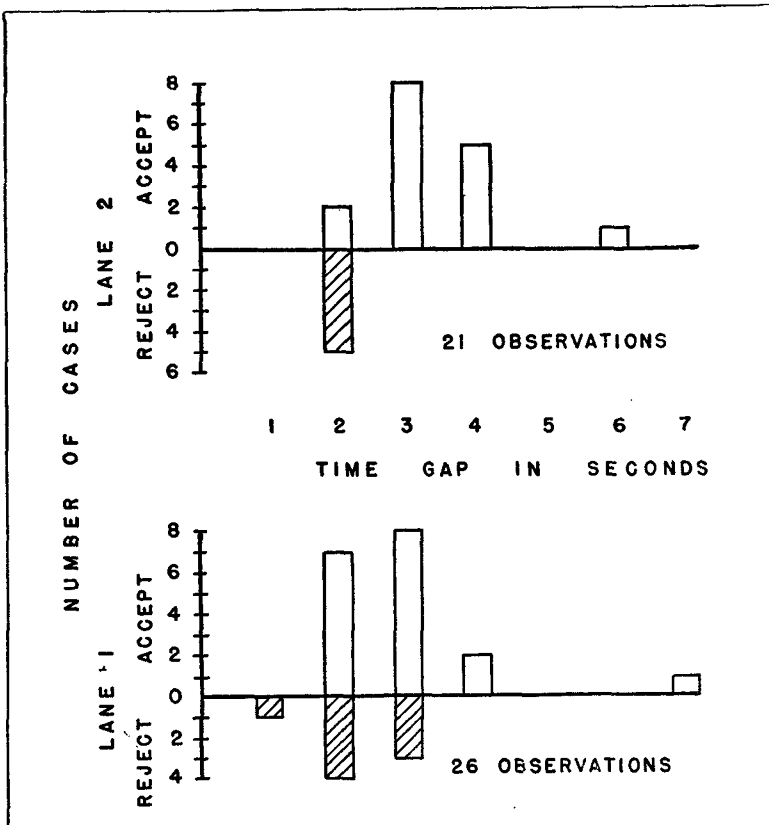

FIGURE 27—Comparison of Accepted and Rejected Time Gaps in Non-Stop Merging by Number of Lanes.

well, as he is overtaking another car under unusual circumstances. These expectations are confirmed by the data, as shown in Table XIII and Figure 27. It will be seen that sixty-four per cent of the "lane two" drivers finding a two second gap will accept, while only twenty-nine percent of the "lane one" drivers meeting a gap of that size will accept. Although there were too few observations to draw conclusions about the influence of lanes, the fact that the data are on the side of logic makes a good check on the method.

Table XXVIII (Appendix II) shows the speed of the merging vehicle as recorded, but there is apparently no correlation between this speed and the length of gap needed for merging.

TABLE XIII

Tabulation of Time Gaps in Non-Stop Merging by Number of Lanes

Time Gap (Seconds)	*Range of Observations (Seconds)*	LANE ONE				LANE TWO			
		Drivers Accepting	*Drivers Rejecting*	*Total*	*Per Cent Accepting*	*Drivers Accepting*	*Drivers Rejecting*	*Total*	*Per Cent Accepting*
1	0–1.4	0	0	0	—	0	1	1	0
2	1.5–2.4	2	5	7	29	7	4	11	64
3	2.5–3.4	8	0	8	100	8	3	11	73
4	3.5–4.4	5	0	5	100	2	0	2	100
5	4.5–5.4	0	0	0	—	0	0	0	—
6	5.5–6.4	1	0	1	100	0	0	0	—
7	6.5–7.4					1	0	1	100
				21				26	

Chapter III

APPLICATION OF MERGING CHARACTERISTICS TO PRACTICAL PROBLEMS

Relation of Ramp Capacity to Volume of Main Traffic Stream

In order to relate ramp capacity and main roadway volume, if the time gap acceptable to merging drivers is known, it is necessary to be able to predict the number of times a gap of this size or greater will appear in a certain length of time. This number will be an indication of the number of cars that will be able to merge successfully in the given time, although it must be pointed out that it does not take into consideration the fact that more than one car will utilize the larger gaps. The need for study of gaps required for the merging of two or more cars is indicated.

The theory of probability has direct application to the merging situations described here. Referring to Figure 1, the relationship may be found between length of time gap, volume of traffic, and frequency of occurrence of time gaps. An indication of the relative capacities of stop and non-stop ramps can be obtained from the number of acceptable gaps occuring in the traffic on the lane next to the ramp. It will be recalled that the values of acceptable time gaps found in the previous chapter were *three seconds* for non-stop merging and *six seconds* for merging from stop-sign locations. The occurrence of gaps of these lengths or greater, at various traffic volumes, may be obtained from Figure 1. As an example, at a volume of 1000 vehicles per lane per hour, time gaps of six seconds or greater will occur with a frequency of 0.19, or at a rate of 1000 x 0.19 = 190 per hour. At the same volume, time gaps of three seconds or greater will occur at a rate of 430 per hour. Similar computations can be made for any given main roadway volume. These values give an approximate indication of ramp capacity, which is further affected by the random arrival of vehicles on the ramp, delays due to stopping of vehicles, and the acceptance of large gaps by two or more vehicles.

Justifying Acceleration Lanes by Calculating Ramp Traffic Delay

The great reduction in ramp capacity, as shown above, when vehicles are required to stop before entering a heavy volume roadway would probably be ample justification for acceleration lanes under certain conditions. Another approach to the question would be from the standpoint of delays to ramp traffic. The formulas derived by Adams for delays to pedestrians crossing a roadway are applicable to this problem. These formulas are as follows:[21]

(1) the proportion of vehicles delayed is

$$1 - e^{-\frac{tv}{3600}}$$

(2) the average delay these suffer is

$$\frac{3600}{ve^{-\frac{tv}{3600}}} - \frac{t}{1 - e^{-\frac{tv}{3600}}} \quad \text{seconds}$$

(3) the average delay suffered by all ramp traffic, including those who find themselves able to merge without waiting, is

$$\frac{3600}{ve^{-\frac{tv}{3600}}} - \frac{3600}{v} - t$$

seconds, in which the symbols have the same meaning as in the Preface.

The first and last equations are of most value in deciding whether or not an acceleration lane is justified. The application of the second equation will be discussed in the next section. Applying the volume figure of 1000 vehicles per lane per hour, as before, produces the following figures: Assuming a ramp entering with an acceleration lane, 57 per cent of the entering vehicles would be delayed, and the average delay for all vehicles would be 1.8 seconds. Assuming the same ramp with a stop sign, all vehicles would be required to stop, but the longer time gap to

[21] Adams, *op. cit.* p. 127.

merge from a stop would cause an additional delay to 81 per cent of the vehicles, and the average delay for all vehicles would be 9.3 seconds in addition to the stopping delay.[22]

A New Approach to Acceleration Lane Design

The length of an acceleration lane is at present calculated from the distance a vehicle needs to accelerate to a given speed, usually chosen as seven-tenths of the design speed. The action thought of is that of matching speed with a car approaching on the main roadway so as to merge either ahead of or behind this car. Under conditions of heavy volume, instead of thinking of "a car approaching," it would be more appropriate to think of "a gap approaching." In that case, the merging problem is not so much a case of matching speeds as calculating how long a delayed vehicle must wait for a gap of appropriate size. This is the application of the second formula presented in the section above.

Assuming peak traffic, the average delay can be calculated for the vehicles that do not at first find a gap. A length of extra lane can then be provided to enable them to maintain a certain minimum speed (for example, fifteen miles per hour) for that length of time. If the speed is allowed to approach zero the length of ramp will be less, but a longer time gap will be needed.

If such extra lanes are not provided, the scarcity of gaps in heavy main roadway traffic will force a vehicle on the ramp to stop. While waiting for the much larger gap needed for merging from a stopped condition, the vehicle will block the ramp, forcing other vehicles to stop. This vicious circle can easily lead to practical blocking of the ramp.

---

[22]EDITOR'S NOTE: For a discussion of the additional delay due to stopping of successive vehicles, see Technical Report No. 1, p. 84.

Chapter IV

SUMMARY AND CONCLUSIONS

In this study of traffic to determine time gaps needed for merging under different conditions, the photographic method was chosen for reasons of manpower and availability of equipment. For a study of this type, a high vantage point is required, thus severely limiting the choice of sites.

Although data of some significance were obtained, the large number of variations between the two sites used had a detrimental effect. Much research of this type is needed under more strictly controlled conditions, as well as more data from any one location.

Analysis of the data obtained shows a large difference between the time gap needed at a stop-sign location and a non-stop location. The majority of drivers will accept a six second gap if stopped, and a three second gap if they are allowed to merge without stopping.

A definite field of application is shown to be open when more data on this subject are obtained. Calculating the number of time gaps of a given size or greater, by the laws of probability, makes it possible to correlate ramp capacity and main roadway volume. Acceleration lanes can be justified on this basis of capacity or from the standpoint of delays due to high volume and small gaps. These delays can be partly eliminated by making added lanes long enough to keep the merging vehicles in motion.

The methods for analysis of merging traffic and prediction of probabilities demonstrated in this study have application to many closely related problems. Studies should be made of the relative efficiency of one- or two-lane ramps. Driver habits in special mixing lanes on express highways are a combination of merging and weaving characteristics. There is considerable controversy over the relative merits of right or left side entrances on high speed roadways which can only be cleared up by field observations. Still another condition needing research along similar lines is the efficiency of traffic circles under various volumes and distribution of traffic.

If this study serves to stimulate interest in additional research on merging traffic, it will have accomplished its main objective.

A Study of Merging Vehicular Traffic Movements

By

RICHARD I. STRICKLAND

A Thesis

Submitted to

BUREAU OF HIGHWAY TRAFFIC

YALE UNIVERSITY

May 1947

Mr. Strickland is at present employed as Assistant Traffic Engineer with the Port of New York Authority.

ACKNOWLEDGMENTS

Much assistance and advice has been received from members of the staff of the Bureau of Highway Traffic in carrying forward the research described in this paper. Thanks are due to Mr. G. A. Drieu and the Connecticut General Life Insurance Company for courtesies extended in the use of their building as a vantage point for the photographic studies.

RICHARD I. STRICKLAND

Yale University
May 1947

INTRODUCTION

Chapter I

Need for Study

In present day construction of new highways and reconstruction of old highways, increasing use is being made of highway facilities allowing continuous flow of intersecting traffic streams. Instead of apportioning right-of-way between intersecting traffic streams by use of traffic signals or other control devices, all streams are allowed continuous movement by means of intersection designs employing traffic rotaries and grade separations with interchange ramps. These facilities change directly intersecting traffic movements into merging and acute-angle crossing maneuvers.

At present few factual data are available concerning merging traffic maneuvers and such data are essential in properly designing continuous-flow traffic facilities.

Purpose of Study

The purpose of this study is to obtain factual data concerning the size of opening between vehicles in a traffic stream that a motorist will accept to merge with that stream. Observations were taken at two points of merging conflict on an urban traffic rotary. In addition, night observations were taken at one of these locations.

Definitions of Terms Used

Merging. For the purpose of this paper merging is the maneuver by which a vehicle joins a stream of traffic by slipping into an opening at an acute angle, whether the purpose be to continue in that stream or to pass through it.

Time Gap. The time elapsed between the arrival of consecutive vehicles at a given point. It is determined in this study from the distance between two consecutive vehicles, front bumper to front bumper (or headlight to headlight in night study), and the speed of the rear vehicle.

Circle Traffic. This term is used to designate traffic circulating around a traffic rotary as distinguished from that just entering the rotary from the radial roads.

Special Techniques for Night Photography

The method of observation at night differed little from the daylight procedure. It was found that maximum exposure of 100 Daylight Weston rated film gave a good recording of vehicle headlights and the streetlights on the section studied. The counter was illuminated with a standard flashlight and recorded brilliantly on the film. A camera speed of 8 frames per second, an aperture opening of f/2.7, and full shutter opening were used.

The analysis procedure was identical with that used for the daylight studies. However, the grid obviously could not be oriented by reference to the geometric layout of the roadway. Instead, the streetlights were used as reference points. The appearance of such lights on the film is shown in Figure 30.

Locations Selected For Study

The nature of this study required that a location be found where a heavy merging movement existed and where a vantage point for the camera was so located that merging movements faced the camera; thus making a night-time study possible. A location meeting these conditions was found in Hartford, Connecticut, where a traffic rotary had been built in 1945. A map of the location is shown in Figure 28.

The two sets of dotted lines in this figure indicate the location of the two merging movements studied. The more extensive daylight study and the night study were made where circle traffic merged into the traffic entering the rotary from Wells Street. Pictures of this site are included in Figure 29, which is a print made from the daylight study film showing one of the observed merging movements.

Figure 30 is a print from the night study film showing a merging maneuver.

This location was ideal for experimenting with night use of the photographic method for two reasons: one, the camera was operated in a lighted room, and two, the many street lights on the rotary aided in aiming the camera and analyzing the films.

The other daylight study was made at the mergence of circle traffic with the traffic from Whitehead Highway. Pictures of this

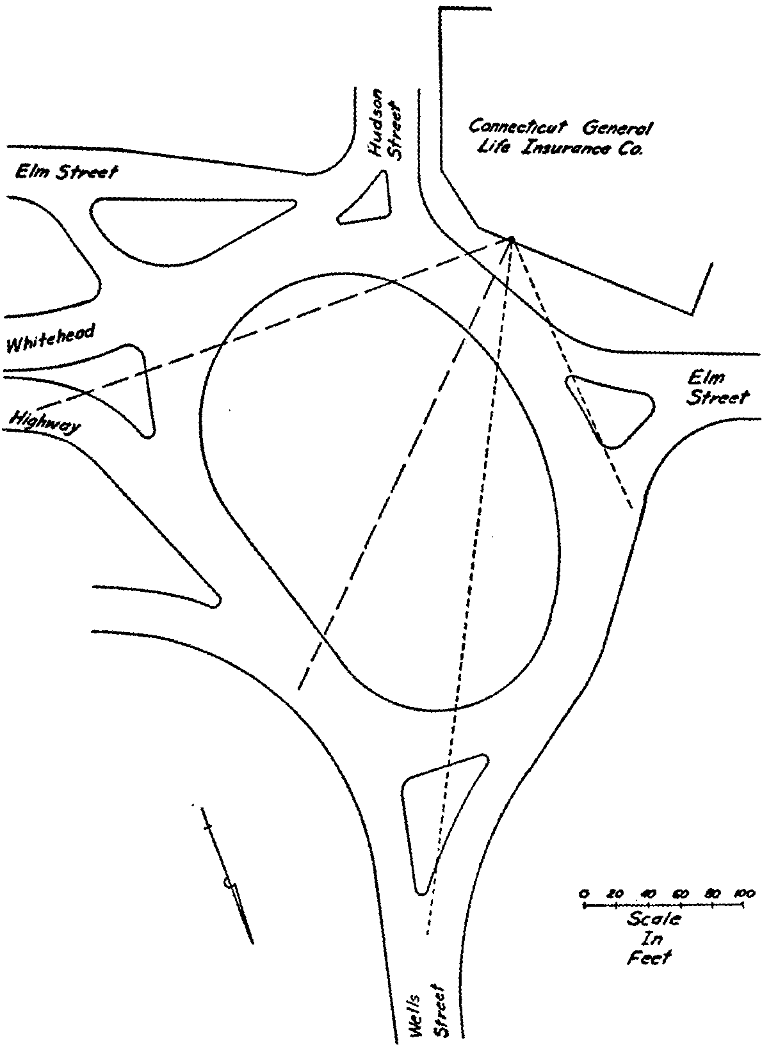

FIGURE 28—Map of Traffic Circle at Which Merging Movements Were Studied.

location are shown in Figure 31, which is a print made from three frames of the study film showing one of the merging movements observed at this point.

It should be noticed that at both merging areas the circle traffic is merging into the traffic entering the rotary. In other words, the rotary actually functioned more like a channelizing island than a rotary. It should also be noticed that at both locations the merging movement is from the left side of the main traffic stream, and probably represents a more difficult maneuver than from the right side.

One limitation of the rotary location in general was that the closeness of the vantage point to the rotary limited the area which could be photographed. It was, therefore, not possible to observe the approach of the merging vehicles over as great a distance as would have been desirable. In another sense, the closeness of the vantage point was beneficial because measurements could be made with greater accuracy.

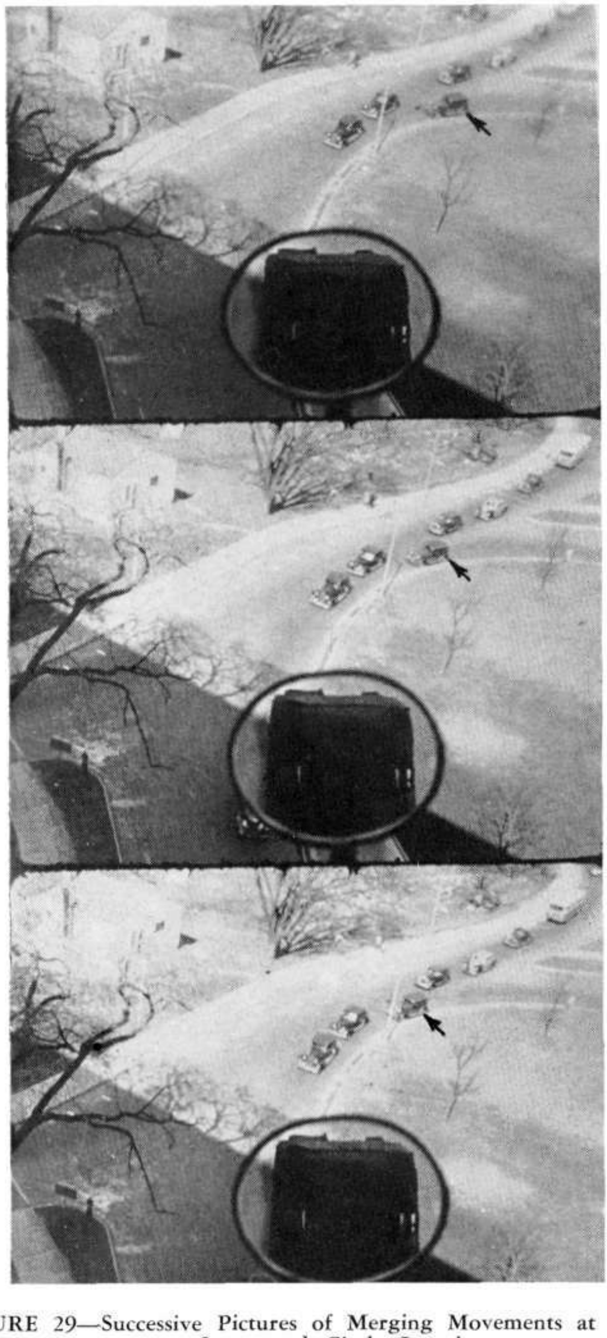

FIGURE 29—Successive Pictures of Merging Movements at Wells Street and Circle Location.

FIGURE 30—Successive Pictures of Merging Movement at Wells Street and Circle Location at Night.

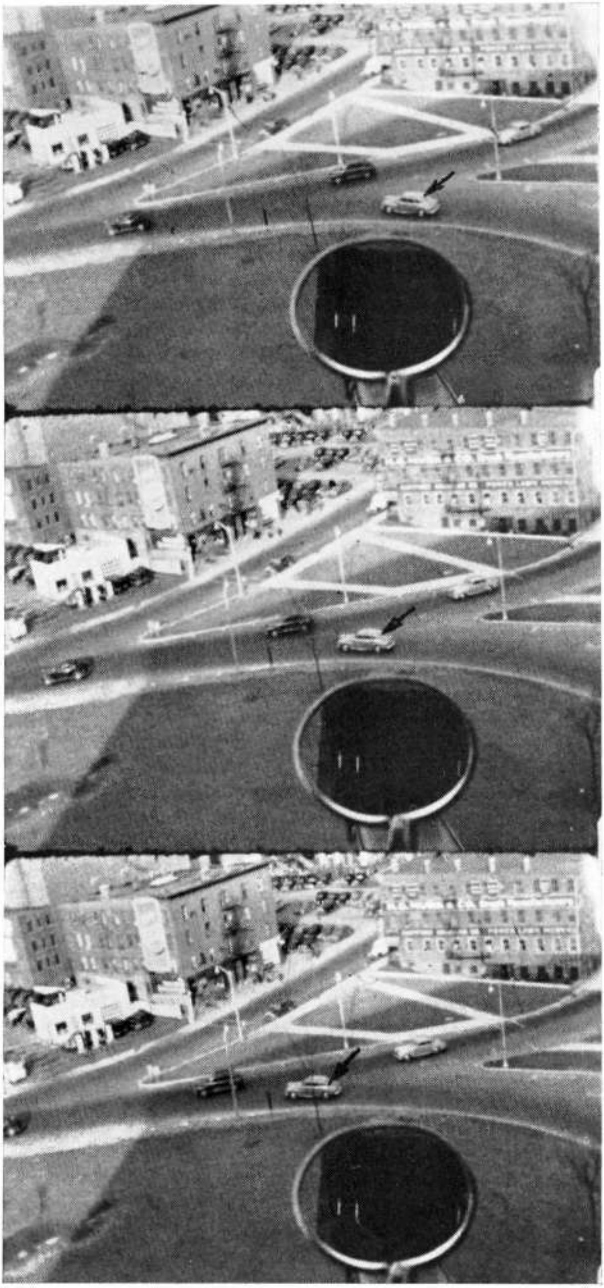

FIGURE 31—Successive Pictures of Merging Movement at Whitehead Highway and Circle Location.

Chapter II

ANALYSIS OF DATA

Analysis of the films yielded a total of 345 observations. After computing the time gaps the resulting data in each study were divided into groups, based upon the speed of the merging vehicles. This was possible because the heavy traffic volumes in the main traffic streams often caused the circle traffic to proceed slowly or actually stop before merging.

It was found that one-tenth second time gap increments were too small to form satisfactory frequency distributions, so observations were grouped about the whole numbers as indicated in the tables to follow.

The analysis procedure was to compare the portion of motorists facing a given gap as to how many accepted the gap and how many rejected the gap. Also, those cases where acceptance of a gap slowed the rear vehicle in that gap were noted. Selection of a time gap suitable for design purposes was based upon whether a gap was accepted by more motorists than rejected it, and the extent to which the acceptance slowed the rear vehicle in the gap.

Daylight Study at Wells Street and Circle

The data obtained at this location are summarized in Table XIV and graphically presented in Figure 32. The three merging vehicle speed groups are 0 to 5, 6 to 14, and 15 to 28 mph. Total observations in each group were respectively 86, 35, and 85.

In the 0 to 5 mph speed group, it appeared that a 6 second gap was indicated because gaps of lesser size were rejected more than 50 per cent of the time. The fact that only two cases were observed wherein the rear vehicle in the gap was slowed would seem to indicate that motorists are very cautious in merging in a traffic stream after stopping.

A marked change was apparent in the 6 to 15 mph speed group. Here a design gap of 3 or 4 seconds was indicated. A 3 second time gap was accepted 4 out of 5 times, but an average reduction of 2.5 mph was caused to rear vehicles in the gaps required to reduce speed (See Table XIV).

TABLE XIV

TABULATION OF TIME GAPS MEASURED IN WELLS STREET & CIRCLE DAYLIGHT MERGING STUDY

Time Gap—Seconds	*1*	*2*	*3*	*4*	*5*	*6*		*Total Accepted Gaps*	*Total Observed Gaps*
Time Gap Range—Seconds	*0–1.4*	*1.5–2.4*	*2.5–3.4*	*3.5–4.4*	*4.5–5.4*	*5.5–6.4*	*Over 6.4*		
SPEED OF MERGING VEHICLE FROM 0 TO 5 MPH									
Number Drivers Accepting	—	—	1	3	1	2	1	8	
No. Cases Rear Vehicle in Accepted Gap Was Slowed	—	—	1	1	0	0	0		
Average Speed Reduction of Vehicles Slowed—MPH	—	—	1	2	—	—	—		
Number Drivers Rejecting	10	38	18	8	3	1	—		
Total Numbers of Observations	10	38	19	11	4	3	1		86
SPEED OF MERGING VEHICLE FROM 6 TO 14 MPH									
Number Drivers Accepting	—	4	4	9	2	4	1	24	
No. Cases Rear Vehicle in Accepted Gap Was Slowed	—	4	2	1	0	0	0		
Average Speed Reduction of Vehicles Slowed—MPH	—	5	2.5	1	—	—	—		
Number Drivers Rejecting	3	7	1	—	—	—	—		
Total Numbers of Observations	3	11	5	9	2	4	1		35
SPEED OF MERGING VEHICLE FROM 15 TO 28 MPH									
Number Drivers Accepting	—	9	18	27	20	8	2	84	
No. Cases Rear Vehicle in Accepted Gap Was Slowed	—	—	5	0	0	0	0		
Average Speed Reduction of Vehicles Slowed—MPH	—	—	3	—	—	—	—		
Number Drivers Rejecting	1	—	—	—	—	—	—		
Total Numbers of Observations	1	9	18	27	20	8	2		86
Total Number of Observations	14	58	42	47	26	15	4	116	206

In the 15 to 28 mph group a design gap of 3 seconds appears necessary. As mentioned previously, the camera location did not allow adequate length of observation of the vehicle desiring

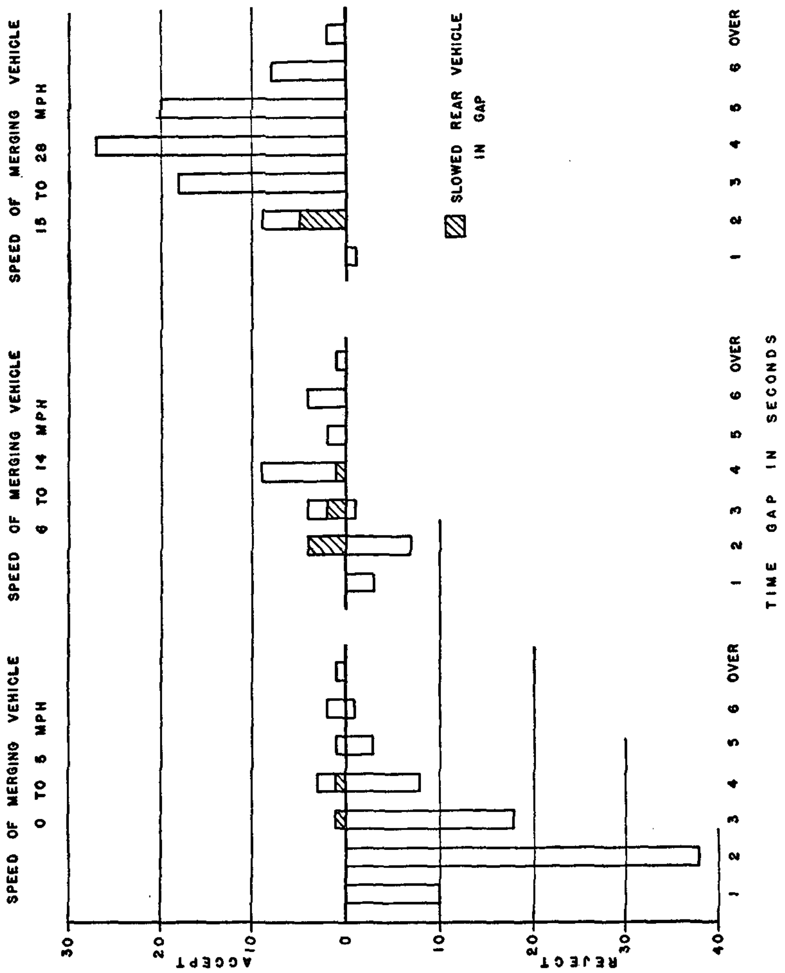

FIGURE 32—Comparison of Accepted and Rejected Time Gaps in Wells Street and Circle Daylight Merging Study.

to merge. Therefore, in the 15 to 28 mph speed range the decision to merge or not had been made and speed so adjusted before coming into the view of the camera. Another difficulty in recording rejection at these speeds would have been the difficulty in telling whether a vehicle was in a position to merge. Because of these limitations, choice of desirable gap was predicated upon the effect on the rear vehicle when a given gap was accepted. A three second gap was therefore selected. The average reduction in speed of the slowed rear vehicle in the two second gaps was 3 mph (See Table XIV).

Daylight Study at Whitehead Highway and Circle

Table XV and Figure 33 present the findings of the daylight

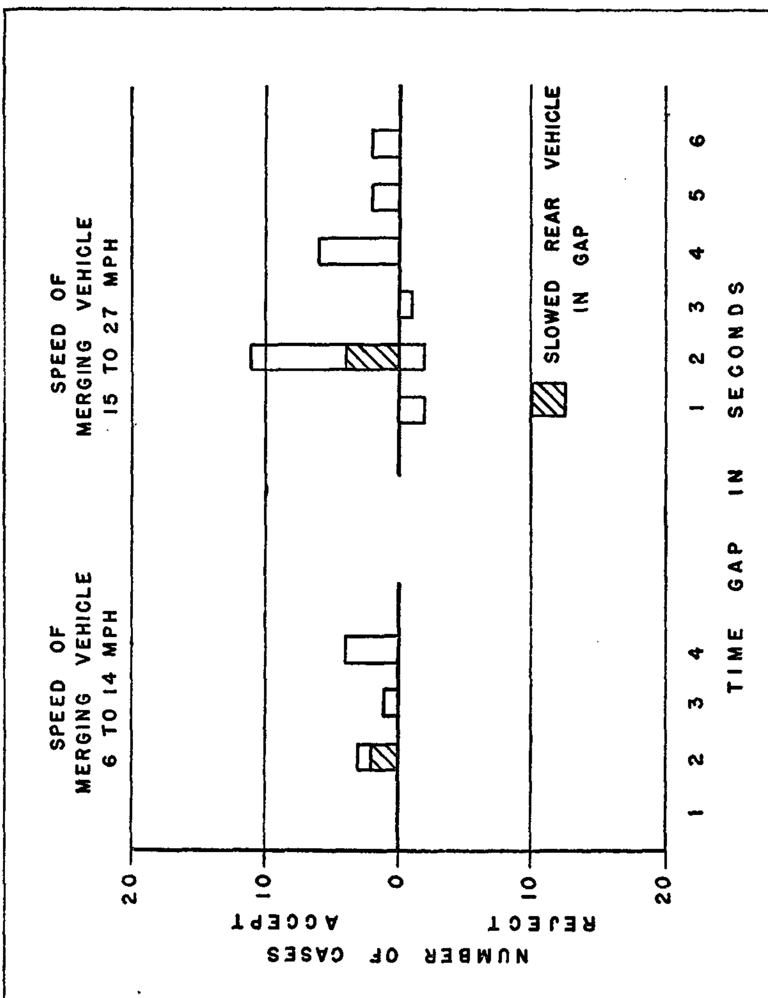

FIGURE 33—Comparison of Accepted and Rejected Time Gaps in Whitehead Highway and Circle Daylight Merging Study.

TABLE XV

Tabulation of Time Gaps Measured in Whitehead Highway and Circle Daylight Merging Study

Time Gap—Seconds	*1*	*2*	*3*	*4*	*5*	*6*		*Total Accepted Gaps*	*Total Observed Gaps*
Time Gap Range—Seconds	*0–1.4*	*1.5–2.4*	*2.5–3.4*	*3.5–4.4*	*4.5–5.4*	*5.5–6.4*	*Over 6.4*		
SPEED OF MERGING VEHICLE FROM 6 TO 14 MPH									
Number Drivers Accepting	—	3	1	4	—	—	—	8	
No. Cases Rear Vehicle in Accepted Gap Was Slowed	—	2	—	—	—	—	—		
Average Speed Reduction of Vehicles Slowed—MPH	—	3	—	—	—	—	—		
Number Drivers Rejecting	—	—	—	—	—	—	—		
Total Numbers of Observations	—	3	1	4	—	—	—		8
SPEED OF MERGING VEHICLE FROM 15 TO 27 MPH									
Number Drivers Accepting	—	11	15	6	2	2	—	36	
No. Cases Rear Vehicle in Accepted Gap Was Slowed	—	4	—	—	—	—	—		
Average Speed Reduction of Vehicles Slowed—MPH	—	1.8	—	—	—	—	—		
Number Drivers Rejecting	2	2	1	—	—	—	—		
Total Numbers of Observations	2	13	16	6	2	2	—		41
Total Number of Observations	2	16	17	10	2	2	—	44	49

Whitehead Highway and Circle study. Conditions at this location were much more favorable to a merging movement. A flatter angle of mergence and a longer merging area existed, and the main stream traffic volume was not quite as great. Consequently, no merging vehicles were required to slow to below 6 miles per hour, and only two speed groups were possible.

Only a few observations were made in the 6 to 14 mph speed group, but a time gap of 3 or 4 seconds was again indicated as desirable.

In the 15 to 27 mph group, a gap of 2 or 3 seconds appears desirable. A three-second time gap should probably be selected, but it is certainly on the conservative side. Of the 11 two-second gaps accepted, in only four instances was the rear vehicle slowed and the average reduction in speed was only 1.8 mph.

Night-Time Study at Wells Street and Circle

When the night-time study at Wells and Circle was contemplated it was thought that a larger time gap might be required at night. No substantiation of this thought was found. However, the street lighting at this location was above average and further study is necessary to determine if similar results would be found at less well-lighted locations and unlighted locations.

Table XVI and Figure 34 present the summarized data for the night study. It should again be noted that the camera was so located that it was not possible to obtain rejects at the higher speeds. Therefore, the selection of the design time gap must be based on the effect of the acceptances on the speeds of the rear vehicles.

For the 0 to 5 mph speed group a six second gap is again indicated as in the daylight study. In the 6 to 14 mph speed group a decision between a three or four second time gap again exists as in the daylight study. The conservative choice once more would be the four second gap, because the sample is so small and the rear vehicle slowed in the three second gap observation was slowed 14 mph.

The data for the 15 to 27 mph group indicated that a three second time gap is entirely adequate and that a two second time gap was again on the borderline. In this case, the reduction in

TABLE XVI

Tabulation of Time Gaps Measured in Wells Street and Circle Night Merging Study

Time Gap—Seconds	*1*	*2*	*3*	*4*	*5*	*6*		*Total Accepted Gaps*	*Total Observed Gaps*
Time Gap Range—Seconds	*0–1.4*	*1.5–2.4*	*2.5–3.4*	*3.5–4.4*	*4.5–5.4*	*5.5–6.4*	*Over 6.4*		
SPEED OF MERGING VEHICLE FROM 0 TO 5 MPH									
Number Drivers Accepting	—	—	—	—	1	2	—	3	
No. Cases Rear Vehicle in Accepted Gap Was Slowed	—	—	—	—	—	—	—		
Average Speed Reduction of Vehicles Slowed—MPH	—	—	—	—	—	—	—		
Number Drivers Rejecting	—	10	14	6	1	—	—		
Total Numbers of Observations	—	10	14	6	2	2	—		34
SPEED OF MERGING VEHICLE FROM 6 TO 14 MPH									
Number Drivers Accepting	—	1	3	2	—	1	1	8	
No. Cases Rear Vehicle in Accepted Gap Was Slowed	—	—	1	—	—	—	—		
Average Speed Reduction of Vehicles Slowed—MPH	—	—	14	—	—	—	—		
Number Drivers Rejecting	2	8	—	1	—	—	—		
Total Numbers of Observations	2	9	3	3	—	1	1		19
SPEED OF MERGING VEHICLE FROM 15 TO 27 MPH									
Number Drivers Accepting	—	2	6	14	7	3	4	36	
No. Cases Rear Vehicle in Accepted Gap Was Slowed	—	2	—	—	—	—	—		
Average Speed Reduction of Vehicles Slowed—MPH	—	2	—	—	—	—	—		
Number Drivers Rejecting	—	1	—	—	—	—	—		
Total Numbers of Observations	—	3	6	14	7	3	4		37
Total Number of Observations	2	22	23	23	9	6	5	47	90

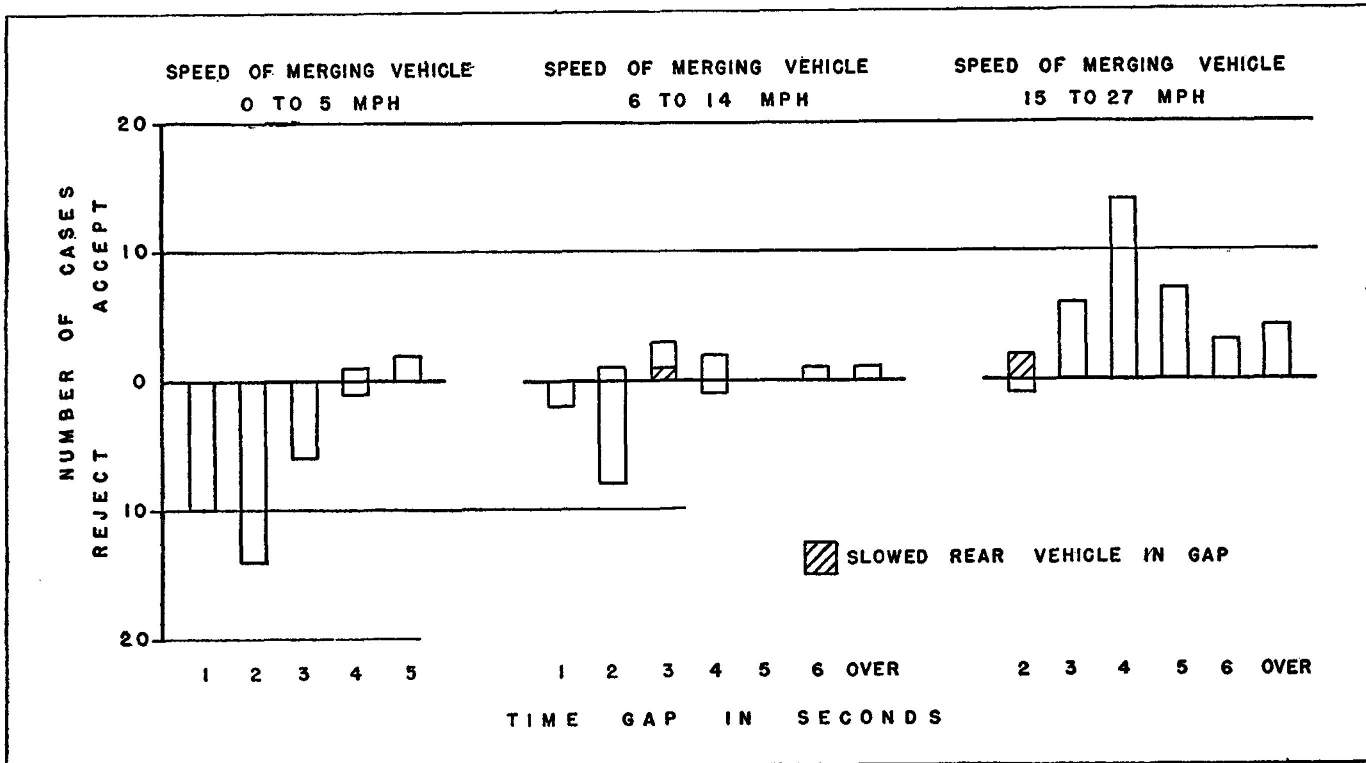

FIGURE 34—Comparison of Accepted and Rejected Time Gaps in Wells Street and Circle Night Merging Study.

speed of the rear vehicle slowed for the two second time gaps averaged 2 mph.

Combined Two-Car Gap Findings

From the three studies discussed, fifteen observations were made of gaps which presented an opportunity for two cars to merge successively. Merging speeds from 11 to 22 mph were

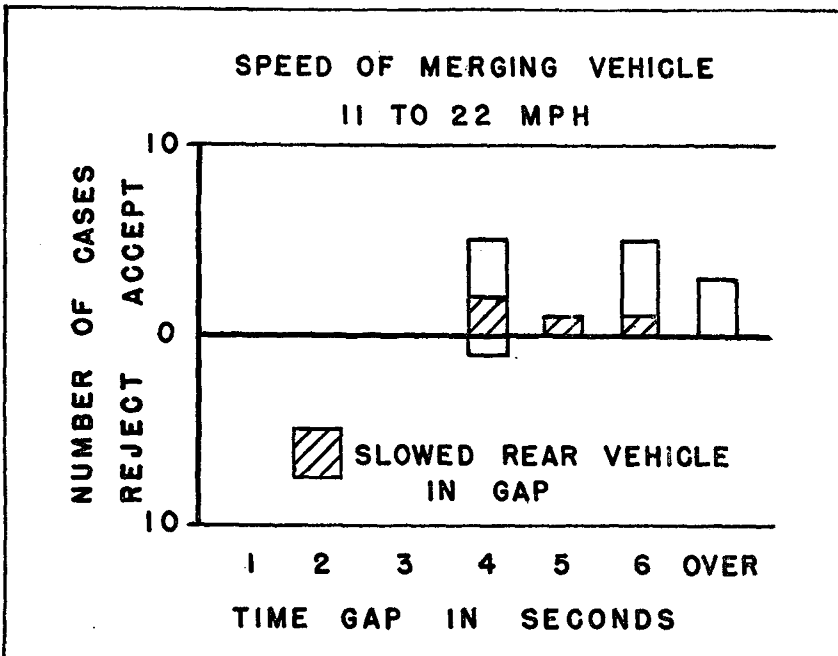

FIGURE 35—Comparison of Accepted and Rejected Time Gaps for Combined Two-Car Gaps.

found. These observations are summarized in Table XVII and Figure 35. The number of observations was insufficient to establish a definite value of acceptable time gap. The average reductions in speed for rear vehicles slowed were 3.5 mph for the four second time gaps and 2 mph for the five and six second time gaps. It is safe to say though that two cars can merge from speeds of from 15 to 35 miles per hour into the same time gap that a single car can from a stopped position.

TABLE XVII

Tabulation of Time Gaps Measured for Combined Two-Car Gaps

Time Gap—Seconds	*1*	*2*	*3*	*4*	*5*	*6*		*Total*
Time Gap Range—Seconds	*0–1.4*	*1.5–2.4*	*2.5–3.4*	*3.5–4.4*	*4.5–5.4*	*5.5–6.4*	*Over 6.4*	
SPEED OF MERGING VEHICLE FROM 11 to 12 MPH								
Number Drivers Accepting	—	—	—	5	1	5	3	
No. Cases Rear Vehicle in Accepted Gap Was Slowed	—	—	—	2	1	1	—	
Average Speed Reduction of Vehicles Slowed—MPH	—	—	—	3.5	2	2	—	
Number Drivers Rejecting	—	—	—	1	—	—	—	
Total Number of Observations	—	—	—	6	1	5	3	15

Chapter III

COMPARISON OF OBSERVATIONS WITH THOSE OF PREVIOUS STUDIES

Gourlay's Observations

Mr. Gourlay's thesis offers direct comparison of merging maneuvers because identical analytical procedures were employed; except that the present study also determined the effect of the acceptance of short gaps upon the rear vehicle in the accepted gap. Gourlay had adequate approach length over which to observe the speed of the merging vehicle, and therefore, was able to obtain "rejects" as well as "accepts" at the higher speeds, which was not possible in this study.

At the stop sign location Gourlay found that the five second time gap margin of acceptance was only five to four while the six second margin was seven to four. He conservatively selected a six second time gap. At the non-stop location, where merging speeds of 11 to 29 mph were recorded, 50 per cent acceptance was found for a two second gap, and the three second gap had an acceptance margin of sixteen to three. Hence, a three second gap was chosen by Gourlay.

Thus, both Gourlay's study and the present study are in agreement on the time gap requirements for merging from a stop and for merging from commonly observed urban speeds.

Wynn's Observations

Both Gourlay's study and the Whitehead Highway and Circle observations in the present study indicated that a three second time gap was readily accepted at non-stop locations, and that possibly a two second time gap might be found adequate if more observations were obtained. A chance to check this possibility existed in the data collected by Wynn. In studying the weaving practices of motorists, Wynn obtained 24 observations of "gap weaves." Such a maneuver is similar to a merging movement as defined herein.

Since these weaving movements observed by Wynn were made under ideal conditions—the weaving vehicle was able to adjust its speed as it traveled parallel to the gap to be entered before entering—analysis of these data should indicate the minimum gap acceptable. The first step in analyzing the data was to change

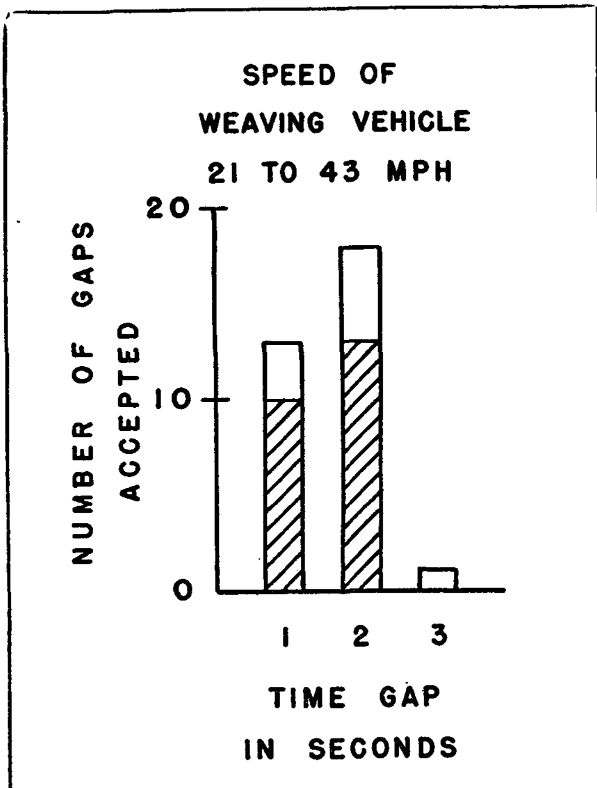

FIGURE 36—Time Gaps for Weaving Maneuvers, Computed from Wynn's Data.

the time-spacings, as indicated by Wynn, to be consistent with the time gaps as defined herein. Wynn's time-spacing is measured between the rear bumper and the front bumper of consecutive cars, instead of from front bumper to front bumper and is computed on the speed of the weaving car. This adjustment was made by adding eighteen feet to the length of the gap as recorded and then computing the time gap from the speed of the rear vehicle in the gap at the beginning of weave. After computing the revised time gaps the data were summarized in the same manner as the original data collected in this study. Determination of the "acceptability" of a time gap had to be based upon the effect of the weaving movements upon the rear vehicles in the gaps.

The summarized data are presented in Table XVIII and Figure

TABLE XVIII

TABULATION OF TIME GAPS COMPUTED FROM WYNN'S DATA

Time Gap—Seconds	*1*	*2*	*3*	*Total*
Time Gap Range—Seconds	*0–1.4*	*1.5–2.4*	*2.5–3.4*	
Weaving Vehicle from 21 to 43 MPH	—	—	—	—
Number Drivers Accepting	11	12	1	—
Number Cases Rear Vehicle in Accepted Gap was Slowed	9	11	—	—
Average Speed Reduction of Vehicles Slowed—MPH	5.4	4.4	—	—
Number Drivers Rejecting	—	—	—	—
Total Number of Observations	11	12	1	24

36.[23] The range in speeds of the weaving vehicles in the group of observations was from 21 to 43 miles per hour. The first point noticed was the large proportion of the merging movements that caused slowing of the rear vehicles in the gaps that were accepted. The amount of slowing appeared great too, as shown in Table XVIII: average reductions in speed of rear vehicles slowed were 6.1 and 4.2 mph respectively, for the one and two second time gaps. Further analysis indicated that all of this slowing was not due to the merging movement alone, because

[23] EDITOR'S NOTE: The anomaly of the two methods of computing time gaps is obvious. The highest value of time-spacing by Wynn's method is 2.7 seconds, to which must be added the time-length of the car (0.35 second) to give a *time gap* of 3.0 seconds. See pp. 37 and 47. By Strickland's method, the corresponding value of time gap for the same maneuver is 2.5 seconds.

the merging vehicles on the average reduced speed 1.5 and 3.1 mph respectively after entering the one and two second time gaps. It appeared that all vehicles concerned were slowing because of some existing condition (probably the presence of the parked car). If the excess slowing of the rear vehicle is assumed to be the net effect due to the merging movement, then average speed reductions of 4.6 mph for the one second gap and 1.1 mph for the two second gap are obtained. In this case a two second gap would seem to be adequate.

This conclusion appears to be supported by the range of observations which Wynn termed gap weaves. The one three-second gap shown in Table XVIII was actually 2.5 seconds and only four other readings greater than two seconds were recorded. These were, 2.1, 2.1, 2.1, and 2.2 seconds. It therefore appears that Wynn did not consider gap conditions to exist for gaps much greater than two seconds.

CHAPTER IV

APPLICATION OF FINDINGS

In this study, as well as in those of Wynn and Gourlay, the significance of time gaps in merging and weaving maneuvers has been demonstrated. As suggested by the previous authors, the concept of time gaps has direct application to the design of acceleration lanes and other roadway facilities. The occurrence of time gaps of different sizes can be predicted by use of the theory of probability, for traffic streams up to the limiting volumes wherein conditions of random spacing no longer prevail.

Further applications will require more detailed study. Empirical data is needed on the merging characteristics of traffic streams of different sizes and the effect of such physical conditions as angle of merging, dimensions of acceleration lanes, and sight distance. Specific information is needed concerning the randomness of arrivals in each stream when two traffic streams merge.

In general, the utility of these findings is in achieving better design and better operation of roadway facilities. The knowledge that approximately twice as large a time gap is needed to merge from stop sign conditions as from moving conditions at speeds of 15 to 40 mph should certainly influence design and redesign of roadways. When new highways are built where heavy traffic volumes exist or can be expected, designs should be such that merging traffic movements are not stopped, but are enabled to merge freely through the use of adequate acceleration lanes, and adequate roadway sections where weaving movements are executed. Likewise, where intersection redesigns are contemplated, proposed channelization should be such that as few traffic movements as possible are regulated by stop signs.

Chapter V

CONCLUSIONS

This study of the time gaps required in a stream of traffic to allow vehicles to merge into that stream has substantiated Gourlay's findings. A six second gap was found to be needed when merging vehicles are forced to stop before merging, and a three second gap was found to be adequate when the merging vehicles entered the main traffic stream at speeds of 15 to 30 miles per hour. There was some indication, however, that in the latter case a two second gap is satisfactory when good merging conditions exist (when the merging vehicle is able to travel almost parallel with the main traffic before entering a gap).

The night study failed to show any significant difference between gap requirements at night and those in daylight. The fact that the roadway section studied was well lighted is stressed, and further study at night is necessary to determine gap requirements in the absence of street lighting. The one significant conclusion to be drawn from the night study was that when good street lighting is provided, the night capacity of a merging facility is little less than the daylight capacity.

The inference can be drawn from the two-car gap findings that two cars can merge at speeds of from 15 to 30 miles per hour into the same gap required by a single car after being required to stop.

The photographic method was successfully used in the night study of a traffic maneuver. Good recording of vehicle headlights and street lights was obtained with 100 Weston Daylight rated film, and the following exposure data: a camera speed of 8 frames per second, a lens opening of f/2.7, and full shutter opening. The use of the photographic method at night is obviously limited to studies wherein vehicle lights are facing the camera.

BIBLIOGRAPHY

Adams, William F., "Road Traffic Considered as a Random Series." *Journal of the Institution of Civil Engineers* (England), 1936.

Greenshields, Bruce D., Donald Schapiro, and Elroy L. Ericksen, *Traffic Performance at Urban Street Intersections*, Technical Report No. 1, Bureau of Highway Traffic, Yale University, 1947.

Holmes, E. H., "Procedure Employed in Analyzing Passing Practices of Motor Vehicles," *Public Roads*, 1939.

Kinzer, John P., "Application of the Theory of Probability to Problems of Highway Traffic." Student Thesis, Brooklyn Polytechnic Institute, 1933. Reviewed by Prof. Lloyd F. Rader, *Proceedings of the Institute of Traffic Engineers*, 1934.

Matson, T. M. and T. W. Forbes, "Overtaking and Passing Requirements as Determined from a Moving Vehicle," *Proceedings of the Highway Research Board*, 1938.

Normann, O. K., "Preliminary Results of Highway Capacity Studies," *Public Roads*, 1939.

———, "Results of Highway Capacity Studies," *Public Roads*, 1942.

Prisk, C. W., "Passing Practices on Rural Highways," *Proceedings of the Highway Research Board*, 1941.

Spears, S. M., "Psychological Factors in Highway Design and Traffic Control Problems," *Proceedings of the Highway Research Board*, 1941.

Appendix I

TABLES XIX TO XXVI

To Wynn's Thesis

WEAVING PRACTICE
ON
ONE-WAY HIGHWAYS

TABLE XIX

Recorded Data — Free Optional Weaves

Number of Weave	Length of Weave (feet)	Weaving Time (frames)	Direction of Weave	Lateral Distance Traveled (feet)	Beginning of Weave: Speed of X (mph)	Beginning of Weave: Speed Differential X - A (mph)	Beginning of Weave: Distance X - A (feet)	Overtaking Time with Speed Differential (frames)	End of Weave: Speed of X (mph)	End of Weave: Speed Differential X - A (mph)
1	207	6	L-R	14	34.5	2	30	15	34.5	2
2	144	4	L-R	12	36	1	22	22	36	1
3	300	10	L-R	11	30	1	27	27	30	1
4	238	7	L-R	12	35	0	52	—	33	1
5	180	5	L-R	15	36	1	27	27	36	3
6	214	6	L-R	11	36	1	52	52	35	2
7	172	5	L-R	15	35	1	25	25	34	0
8	261	8	L-R	9	30	—1	24	—	34	0
10	222	6	L-R	10	37	3	46	15.3	37	3
11	186	6	L-R	9	31	0.5	32	64	31	0.5
12	316	8	L-R	8	39.5	4.5	60	13	39.5	4.5
13	216	6	R-L	8	36	1	15	15	36	1
14	108	3	L-R	11	36	5	15	3	36	5
16	165	7	L-R	6	23	0	4	—	25	4
18	170	5	L-R	11	34	3	9	3	33	3
19	251	7	R-L	13	38	5	19	3.8	33	1
21	185	5	L-R	8	36	1	42	42	38	3
22	148	5	R-L	10	29	5	24	4.8	31	7
23	231	6	R-L	8	38.5	3.5	44	12.5	38.5	3.5
25	244	8	L-R	7	27	—1	30	—	34	7

TABLE XIX (Cont'd)

Number of Weave	Length of Weave (feet)	Weaving Time (frames)	Direction of Weave	Distance Lateral Traveled (feet)	Beginning of Weave: Speed of X (mph)	Beginning of Weave: Speed Differential X-A (mph)	Beginning of Weave: Distance X-A (feet)	Overtaking Time with Speed Differential (frames)	End of Weave: Speed of X (mph)	End of Weave: Speed Differential X-A (mph)
26	154	5	R-L	9	30	4	40	10	32	7
27	129	3	R-L	6	42	4.5	17	3.8	44	6.5
30	204	6	L-R	12	34	—1	2	—	35	1
31	277	7	L-R	7	40	2.5	33	13.2	39	1.5
33	293	9	L-R	10	30	0	30	—	34	3.5
34	163	5	R-L	8	32.5	2.5	22	8.8	33.5	4.5
37	155	5	L-R	8	31	4	54	13.5	31	6
39	236	7	L-R	10	33	—1	38	—	34	5
40	260	8	L-R	14	32.5	0.5	18	36	32.5	1.5
41	293	9	L-R	9	33	2	27	13.5	32	2
43	225	6	L-R	13	38	8	47	6	38	8
44	184	5	L-R	9	36	5	37	7.4	38	6
52	159	4	L-R	10	39	3	34	11.3	41	5
53	147	3	R-L	9	36	1	19	19	37	4
57	149	3	L-R	7	28	2	22	11	31	5
58	198	5	L-R	8	37	0.5	41	82	42	5.5
59	161	5	L-R	8	31	1	29	29	34	4
60	161	4	R-L	13	40	7	35	5	41	8
61	272	8	L-R	11	34	4	55	14	34	4
62	252	7	L-R	6	36	0	26	—	36	0
63	231	7	L-R	7	33	2	27	13.5	33	2
65	111	3	L-R	10	36	3.5	17	5	38	5.5
66	258	6	L-R	8	44	12	85	7	42	10
67	277	7	L-R	8	39.5	1.5	42	14	39.5	1.5
68	149	4	L-R	6	37	4	26	6.5	37.5	4.5

TABLE XIX (Cont'd)

Number of Weave	*Length of Weave (feet)*	*Weaving Time (frames)*	*Direction of Weave*	*Lateral Distance Traveled (feet)*	*Beginning of Weave: Speed of X (mph)*	*Beginning of Weave: Speed Differential X - A (mph)*	*Beginning of Weave: Distance X - A (feet)*	*Overtaking Time with Speed Differential (frames)*	*End of Weave: Speed of X (mph)*	*End of Weave: Speed Differential X - A (mph)*
70	131	6	L-R	7	37	2	28	14	39	5
71	170	5	L-R	8	33	3	25	8.3	35	6
72	185	5	L-R	8	37	3	40	13.3	37	4
74	198	6	R-L	10	35	1	37	37	30	6
75	266	7	L-R	7	38	1	42	42	38	2
76	297	8	L-R	8	36	0	32	—	38	3
77	390	11	R-L	11	40	2	32	16	36	3
79	445	12	L-R	6	39	3	34	11.3	35	2
80	308	7	L-R	14	44	2	40	20	44	0
81	264	7	R-L	10	37	3	42	14	38	4
84	449	10	R-L	12	46	—	—	—	45	—
88	425	10	R-L	11	40	—	—	—	44	—
90	364	12	R-L	11	28	—	—	—	31	—
99	184	4	L-R	10	46	3	40	13.3	46	5
136	134	4	L-R	10	45	9	22	2.4	44	8
143	122	4	L-R	9	30.5	8.5	26	3	30.5	7.5
156	238	7	L-R	7	42	8	42	5.25	21	1
181	168	4	L-R	10	42	2	10	5	42	2
203	157	4	L-R	11	42	9	44	5	37	10

TABLE XX

Recorded Data — Retarded Optional Weaves

					Beginning of Weave					End of Weave			
Number of Weave	*Length of Weave (feet)*	*Weave Time (frames)*	*Lateral Distance Traveled (feet)*	*Direction of Weave*	*Speed of X (mph)*	*Speed Differential X-A (mph)*	*Speed Differential X-C (mph)*	*Distance X-A (feet)*	*Distance X-C (feet)*	*Speed of X (mph)*	*Speed Differential X-A (mph)*	*Speed Differential X-C (mph)*	*Distance X-C (feet)*
9	132	4	9	L-R	33	3	— 5.5	17	36	34	4	— 1	72
15	220	6	6	L-R	40	8	5	64	34	35	8	1	25
32	108	3	9	L-R	35	3	— 4	17	6	37	5	— 1	12
42	124	4	11	L-R	28	0	—11	19	0	34	4	— 5	30
45	204	6	9	L-R	34	4	5	42	12	34	4.5	— 1	30
47	87	3	6	L-R	29	5	— 8.1	22	—18	29	8	— 7	6
48	113	4	8	L-R	29	1	— 4	15	14	27	5	0	25
49	224	7	10	L-R	29	0	— 7	40	22	36	8	— 1	45
55	174	5	11	L-R	35	3	0	40	22	34	4	0	20
56	291	8	6	L-R	36	2	— 1.5	21	— 5	37	3	— 1	6
68	120	3	14	L-R	29	4	— 4	21	6	31	6	— 3	16
73	219	7	11	L-R	32	2	— 3	35	2	30	0	1	16
78	143	4	7	L-R	35	9	0	39	19	37	12	2	17
82	140	4	10	L-R	35	3	— 9	20	60	35	3	6	92
93	159	5	8	L-R	33	—	1	—	20	30	—	— 3	24
94	195	5	10	L-R	38	3	— 2	25	5	40	3	0	18
96	139	5	10	L-R	30	25	—15	98	—15	25	—	—13	49
164	222	6	8	L-R	40	5	0	58	36	33	3	3	20

TABLE XXI

Recorded Data — Conflict: Optional Weaves

Number of Weave	Length of Weave (feet)	Weave Time (frames)	Lateral Distance Traveled (feet)	Direction of Weave	Beginning of Weave: Speed of X (mph)	Beginning of Weave: Speed Differential X-A (mph)	Beginning of Weave: Speed Differential X-B (mph)	Beginning of Weave: Distance X-A (feet)	Beginning of Weave: Distance X-B (feet)	End of Weave: Speed of X (mph)	End of Weave: Speed Differential X-A (mph)	End of Weave: Speed Differential X-B (mph)	End of Weave: Distance X-B (feet)
20	225	6	11	L-R	37.5	0.5	10	30	—5	37.5	5.5	10	—62
24	271	7	—10	L-R	39	1	4	38	3	38	0	3	—27
29	180	4	—8	R-L	45	7	7.5	52	3	45	7	7.5	—27
35	208	6	8	L-R	35	5	3	38	3	34.5	5.5	4.5	—8
46	152	4	—12	R-L	38	1	3	14	—16	38	5	4	—30
64	165	5	8	L-R	31	—1	—2	24	—36	35	3	2	—32
85	404	10	8	L-R	40	—	1	—	0	41	—	1	—10
87	261	5	12	L-R	52	—	14	—	—32	53	—	13	—99
89	362	9	—10	R-L	42	—	8	—	1	35	—	3	—67
95	140	3	—10	R-L	47	—	9.5	—	—7	45	—	7.5	—32
97	434	10	—10	R-L	41	—	—1.5	—	—66	44	—	1.5	—76
98	397	11	—9	R-L	35	—	—2	—	—32	37	—	0	—32
100	190	4	—9	R-L	45	4	10	23	2	50	9	14	—49

TABLE XXII

Recorded Data — Gap Optional Weaves

Number of Weave	Length of Weave (feet)	Weave Time (frames)	Length of Gap (feet)		Lateral Distance Travelled (feet)	Direction of Weave	Beginning of Weave							End of Weave					
								Speed Differential			Spacing				Speed Differential			Spacing	
			Start	End			Speed of X (mph)	X - A (mph)	X - B (mph)	X - C (mph)	X - A (feet)	X - B (feet)	X - C (feet)	Speed of X (mph)	X - A (mph)	X - B (mph)	X - C (mph)	X - B (feet)	X - C (feet)
17	344	8	82	107	9	L-R	43	7	5	1	70	5	69	43	9	5	1	—32	57
28	117	3	90	102	6	L-R	39	10	6.5	2	29	—30	42	39	11	6.5	2	—47	37
50	140	4	75	72	10	L-R	35	4	—2	0	32	—33	24	35	4	0	0	—30	24
51	161	5	78	86	8	L-R	32	1	—2	—5	45	—44	16	32.5	1.5	—1.5	—3.5	—35	33
54	132	4	83	88	9	L-R	34	2	2.5	2	24	—38	27	34	2	—2.5	2	—46	24
83	182	5	43	38	10	L-R	37	3	—1	—1	20	— 7	18	36	4	—2	2	— 4	16
86	320	8	67	73	9	L-R	38	0	0	—2	22	—17	32	42	—2	3	2	—22	33
91	304	8	90	80	10	L-R	38	5	—9	1	50	—42	30	38	7	0	1	—37	25
92	258	7	130	116	10	L-R	38	—	—	—4	—	—110	2	35	0	1	—5	—77	21

TABLE XXIII

Recorded Data — Free Forced Weaves

Number of Weave	*Length of Weave (feet)*	*Weave Time (frames)*	*Speed of X (mph)*	*Spacing X-A (feet)*	*Speed of X (mph)*
195	189	5	39	192	38
194	157	7	24	180	22
193	127	6	23	145	23
192	87	3	30	102	28
191	133	4	33	137	34
190	130	4	35	120	30
185	120	3	40	130	40
184	123	3	42	152	40
183	200	5	42	228	38
178	175	6	33	195	25
175	135	3	45	122	45
174	152	4	38	172	38
172	146	4	38	162	36
171	186	5	40	185	36
170	90	3	30	100	30
162	126	4	33	135	32
161	140	4	36	142	34
160	135	4	34	152	33
147	156	4	39	192	39
146	91	4	25	99	22
139	79	3	27	83	26
132	115	3	38	110	32
130	118	4	31	138	28
125	105	3	35	111	35
124	140	4	35	140	35
122	134	4	35	147	32
121	105	3	35	121	35
120	134	4	34	157	33
119	81	3	26	74	28
112	140	4	35	162	35
109	140	6	35	142	35

TABLE XXIV

RECORDED DATA — RETARDED FORCED WEAVES

Number of Weave	Length of Weave (feet)	Weave Time (frames)	Beginning of Weave: Speed of X (mph)	Beginning of Weave: Speed Differential X - C (mph)	Beginning of Weave: Spacing X - A (feet)	Beginning of Weave: Spacing X - C (feet)	End of Weave: Speed of X (mph)	End of Weave: Speed Differential X - C (mph)	End of Weave: Spacing X - C (feet)
204	145	4	30	0	148	5	27	— 5	12
202	155	6	28	1	157	8	25	— 2	12
200	139	5	31	2	148	20	25	— 4	26
199	203	7	34	3	207	24	27	— 1	17
198	92	3	31	— 2	94	2	30	— 5	13
196	100	3	35	— 2	117	20	32	— 6	28
187	109	3	37	— 1	114	6	36	— 2	14
182	250	6	44	1	272	28	40	— 3	52
180	82	3	37	— 3	117	24	38	— 3	32
179	116	3	40	3	140	16	36	— 2	12
177	125	4	31	— 6	140	15	32	— 9	44
176	76	2	38	— 2	94	16	38	— 2	20
169	62	7	30	—13	70	8	32	—11	32
168	76	3	25	—17	67	12	26	—17	62
159	128	4	32	— 3	150	5	33	— 2	15
152	157	6	30	3	157	25	25	0	17
144	92	3	30	—11.5	88	9	31	—10.5	42
141	110	4	28	— 1	115	20	27	1	22
140	110	4	30	4	104	30	25	0	22
135	145	4	36	— 7	150	6	37	— 6	29
127	149	6	23	— 6	139	2	27	— 5	28
116	125	4	32	— 8	138	0	31	— 9	37
107	85	30	30	0	84	7	27	— 3	11
103	160	4	40	— 2	170	51	40	— 2	60
101	97	3	32	— 4	107	29	33	— 3	39

TABLE XXV

Recorded Data — Conflict Forced Weaves

Number of Weave	Length of Weave (feet)	Weave Time (frames)	Beginning of Weave: Speed of X (mph)	Beginning of Weave: Speed Differential X - B (mph)	Beginning of Weave: Spacing X - A (feet)	Beginning of Weave: Spacing X - B (feet)	End of Weave: Speed of X (mph)	End of Weave: Speed Differential X - A (mph)	End of Weave: Spacing X - B (feet)
189	161	4	40	4	186	10	41	2	22
173	108	3	36	2	122	15	36	4	26
163	128	4	32	—3	118	12	32	3	12
137	205	5	41	3	201	14	41	1	28
126	193	6	35	0	206	21	32	1	22
117	214	5	44	4	235	7	42	6	26
111	213	5	42.5	0.5	214	0	42.5	5	3
110	172	4	43	1	170	0	43	1	4
104	123	3	41	2	151	32	41	5	44

TABLE XXVI
Recorded Data — Gap Forced Weaves

Number of Weave	Length of Weave (feet)	Weave Time (frames)	Size of Gap (feet) Start	Size of Gap (feet) End	Beginning of Weave: Speed of X (mph)	Speed Differential X-B (mph)	Speed Differential X-C (mph)	Spacing X-A (feet)	Spacing X-B (feet)	Spacing X-C (feet)	End of Weave: Speed of X (mph)	Speed Differential X-B (mph)	Speed Differential X-C (mph)	Spacing X-B (feet)	Spacing X-C (feet)
201	147	5	47	52	32	4	2	180	—17	12	26.5	1.5	— 0.5	—26	8
102	102	3	134	107	34	—8	—1	100	—72	44	34	—8	— 1	—42	47
105	191	5	56	56	41	—	6	249	0	38	36	3	— 1	—16	22
113	203	5	64	76	41	1	4	217	—14	32	40	5	0	—32	26
114	115	3	86	83	40	0	0	107	—38	30	35	—3	1	—38	27
118	196	6	52	89	34	—6	—9	222	—27	7	31	1	—10	—12	59
123	148	4	36	36	39	3	2	146	— 6	12	35	0	1	—11	7
128	100	4	50	53	25	—3	0	108	—10	22	25	1	— 3	—10	25
129	113	5	52	79	21	—2	—4	104	—17	17	25	2	— 5	—14	47
131	176	5	84	81	38	—2	—2	195	—32	34	33	—2	— 4	—19	44
134	150	4	58	52	39	—1	3	145	—26	14	36	1	0	—24	10
138	165	4	80	88	43	3	5	196	— 4	58	40	5	0	—22	48
145	118	4	92	91	30	—9	—8	128	—59	15	30	—5	— 7	27	46
146	201	6	78	94	38	—1	—2	202	—44	16	31	—1	0	—58	18
148	101	3	38	48	32	—4	—6	114	—18	2	35	—1	— 3	—14	16
149	107	3	64	56	35.5	0.5	5.5	222	—19	27	35.5	1.5	1.5	—22	16
150	146	4	74	78	39	9	6	152	0	56	35	7	0	—28	32
151	80	3	49	48	29	1	2	90	— 9	22	25	—1	— 3	— 8	22
154	147	6	61	49	32	—3	3	157	—25	18	22	0	— 4	—12	19
158	207	6	55	64	41	3	5	218	—38	17	17	—6	— 5	—30	16
167	124	4	38	54	33	—1	—2	138	—18	2	29	0	— 7	—18	18
186	79	3	35	53	25	—3	—9	75	—15	2	28	0.5	— 9	— 6	29
188	190	5	39	70	38	6	—2	184	4	25	39	4	0	—24	28
197	179	5	39	46	38	—1	2	185	— 6	15	36	0	— 1	—11	17

Appendix II

TABLES XXVII - XXVIII

To Gourlay's Thesis

MERGING TRAFFIC CHARACTERISTICS

TABLE XXVII

SUMMARY OF OBSERVATIONS AT STOP-SIGN LOCATION

Obs. No.	*Time Gap Observed (seconds)*	*Accept*	*Reject*	*Obs. No.*	*Time Gap Observed (seconds)*	*Accept*	*Reject*
1	8.0	x		28	4.5	x	
2	2.5		x	29	2.5		x
3	1.9		x	30	6.0	x	
4	3.8	x		31	5.6	x	
5	4.6	x		32	6.4	x	
6	5.5		x	33	3.2		x
7	9.7	x		34	2.8		x
8	2.3		x	35	5.6	x	
9	4.8		x	36	4.0		x
10	4.0		x	37	4.3	x	
11	5.6		x	38	4.7	x	
12	8.6	x		39	2.6		x
13	5.4		x	40	2.3		x
14	8.0	x		41	7.6	x	
15	9.0	x		42	9.1	x	
16	6.7	x		43	5.2		x
17	5.9	x		44	5.7		x
18	8.9	x		45	2.2		x
19	3.4		x	46	4.7	x	
20	4.9		x	47	3.4	x	
21	6.8	x		48	5.9	x	
22	7.0	x		49	4.7	x	
23	6.9		x	50	2.9		x
24	5.7		x	51	2.4		x
25	4.0		x	52	3.4		x
26	6.0	x		53	6.5	x	
27	4.0	x		54	7.0		x

TABLE XXVIII

SUMMARY OF OBSERVATIONS AT NON-STOP LOCATION

Obs. No.	*Lane No.*	*Speed of Merging Vehicle (m.p.h.)*	*Time Gap Observed (seconds)*	*Accept*	*Reject*
1	1	20	6.0	x	
2	2	18	2.9	x	
3	2	21	2.0	x	
4	1	21	3.5	x	
5	2	23	3.1		x
6	2	18	1.5	x	
7	1	18	1.5		x
8	1	19	1.9		x
9	2	15	2.1	x	
10	1	24	2.4	x	
11	2	20	2.3	x	
12	1	17	1.7		x
13	2	17	1.7		x
14	2	8	3.4		x
15	2	10	2.7		x
16	2	15	2.2		x
17	1	26	1.7		x
18	2	24	3.3	x	
19	2	16	2.2	x	
20	2	24	2.8	x	
21	2	18	1.2		x
22	2	24	2.4	x	
23	2	22	3.8	x	
24	2	15	1.6		x
25	2	17	3.3	x	
26	2	23	1.6		x
27	2	22	2.0	x	
28	1	20	3.9	x	
29	1	22	3.5	x	
30	2	24	2.7	x	
31	1	22	2.9	x	
32	1	20	3.1	x	
33	1	18	1.9		x
34	1	24	3.1	x	
35	2	21	2.8	x	
36	2	20	4.1	x	
37	2	22	2.5	x	
38	1	21	3.7	x	
39	1	25	2.7	x	
40	1	18	2.9	x	
41	1	21	1.9	x	
42	1	29	3.7	x	
43	2	19	6.6	x	
44	1	18	2.6	x	
45	1	17	3.3	x	
46	2	11	2.9	x	
47	1	26	2.9	x	

Appendix III

TABLES XXIX TO XXXIII

To Strickland's Thesis

MERGING VEHICULAR MOVEMENTS

TABLE XXIX

Gap Observations — Wells Street and Circle Daylight Study

No.	Accept(A) or Reject (R)	Start of Merge V_m	G_f	$V_{r.v.}$	G_s	End of Merge V_m	$V_{r.v.}$
1	A	13	225	11	13.9	20	19
2	R	5	51	14	2.5	—	—
3	A	18	185	20	6.3	—	—
4	A	14	120	14	5.8	18	14
5	A	9	40	14	1.9	11	11
6	A	21	68	20	2.3	19	19
7	R	6	55	20	1.9	—	—
8	A	0	103	18	3.9	—	—
9	A	15	164	18	6.2	—	—
10	A	12	99	15	4.5	16	24
11	A	21	121	14	5.9	17	19
12	A	17	67	15	3.0	19	18
13	A	16	93	21	3.0	22	21
14	A	19	140	17	5.6	19	15
15	A	15	33	13	1.7	12	11
16	A	21	81	17	3.2	—	—
17	A	16	54	15	2.5	17	22
18	A	12	66	12	3.7	17	14
19	R	5	70	19	2.5	—	—
20	A	5	69	17	2.8	18	16
21	R	0	78	20	2.7	—	—
22	R	0	87	21	2.8	—	—
23	R	0	50	22	1.5	—	—
24	A	17	78	22	2.4	19	19
25	R	5	79	20	2.7	—	—
26	R	2	80	20	2.7	—	—
27	R	1	58	22	1.8	—	—
28	A	15	95	18	3.6	17	16
29	A	28	93	16	4.0	26	17
30	A	17	70	15	3.2	16	15
31	R	0	46	17	1.8	—	—
32	R	0	43	17	1.7	—	—
33	R	0	37	19	1.3	—	—
34	R	0	91	17	3.7	—	—
35	R	0	72	23	2.1	—	—
36	R	0	43	22	1.3	—	—
37	R	0	63	22	2.0	—	—
38	R	0	87	20	3.0	—	—
39	R	0	53	19	1.9	—	—
40	R	0	43	18	1.7	—	—

TABLE XXIX (Cont'd)

No.	Accept(A) or Reject (R)	Start of Merge V_m	G_f	$V_{r.v.}$	G_t	End of Merge V_m	$V_{r.v.}$
41	R	0	53	19	1.9	—	—
42	R	0	43	18	1.6	—	—
43	R	0	67	21	2.2	—	—
44	R	0	37	20	1.3	—	—
45	R	0	67	21	2.2	—	—
46	R	0	37	20	1.3	—	—
47	A	0	83	16	3.5	12	17
48	R	0	83	16	3.5	—	—
49	R	0	40	18	1.5	—	—
50	R	1	72	19	2.6	—	—
51	R	0	56	20	1.9	—	—
52	R	0	160	20	5.5	—	—
53	A	20	118	21	3.8	19	20
54	A	25	69	20	2.4	21	19
55	R	9	46	21	1.5	—	—
56	A	0	102	19	3.7	20	17
57	A	18	163	21	5.3	18	19
58	A	24	143	20	4.9	—	—
59	A	20	84	18	3.2	20	18
60	A	21	114	16	4.9	—	—
61	A	22	134	21	4.3	—	—
62	A	19	115	24	3.3	—	—
63	R	13	43	23	1.3	—	—
64	A	15	110	20	3.8	—	—
65	R	18	54	26	1.4	—	—
66	A	21	126	22	3.9	—	—
67	A	20	70	17	2.8	21	19
68	A	20	96	16	4.1	—	—
69	R	5	59	17	2.4	—	—
70	A	7	51	18	1.9	11	10
71	R	0	51	18	1.9	—	—
72	A	23	90	14	4.4	—	—
73	A	18	67	19	2.4	18	19
74	A	13	85	18	3.2	15	15
75	A	24	55	21	1.8	25	21
76	R	13	35	19	1.3	—	—
77	A	14	96	18	3.6	15	13
78	A	13	88	14	4.3	—	—
79	A	25	132	17	5.3	—	—
80	R	0	95	17	3.8	—	—
81	R	0	89	21	2.9	—	—
82	R	0	59	20	2.0	—	—
83	R	0	61	22	1.9	—	—
84	R	0	81	19	2.9	—	—
85	R	0	70	20	2.4	—	—

TABLE XXIX (Cont'd)

No.	Accept(A) or Reject (R)	Start of Merge V_m	G_f	$V_{r.v.}$	G_s	End of Merge V_m	$V_{r.v.}$
86	R	0	130	18	4.2	—	—
87	R	0	94	19	3.4	—	—
88	R	0	73	20	2.5	—	—
89	R	0	48	22	1.5	—	—
90	R	0	103	21	3.3	—	—
91	R	0	37	22	1.1	—	—
92	R	0	93	21	3.0	—	—
93	R	0	75	22	2.3	—	—
94	R	0	63	21	2.0	—	—
95	R	0	96	21	3.1	—	—
96	R	0	47	23	1.4	—	—
97	A	19	66	19	2.4	17	14
98	A	16	114	20	3.9	—	—
99	A	19	90	17	3.6	—	—
100	A	16	126	17	5.0	—	—
101	A	16	124	17	5.0	—	—
102	A	21	102	23	3.5	—	—
103	R	0	67	21	2.2	—	—
104	R	0	65	18	2.5	—	—
105	R	8	60	22	1.9	—	—
106	A	8	50	13	2.6	16	11
107	R	0	81	12	4.6	—	—
108	A	21	81	12	4.6	—	—
109	A	21	91	21	3.0	—	—
110	R	11	77	23	2.3	—	—
111	A	18	80	23	2.4	—	—
112	A	13	80	13	4.2	—	—
113	R	0	133	21	4.3	—	—
114	R	0	48	22	1.5	—	—
115	R	0	71	23	2.1	—	—
116	A	0	116	17	4.7	—	—
117	R	0	116	17	4.7	—	—
118	R	0	125	20	4.3	—	—
119	R	0	83	19	3.0	—	—
120	R	0	70	20	2.4	—	—
121	R	0	40	22	1.2	—	—
122	R	0	61	22	1.9	—	—
123	R	0	118	21	3.8	—	—
124	R	0	79	21	2.6	—	—
125	R	0	42	22	1.3	—	—
126	A	19	101	18	3.8	—	—
127	A	24	82	17	3.3	—	—
128	A	19	104	20	3.5	—	—
129	R	0	35	21	1.5	—	—
130	R	0	143	19	5.1	—	—

TABLE XXIX (Cont'd)

No.	Accept(A) or Reject (R)	Start of Merge V_m	G_f	$V_{r.v.}$	G_s	End of Merge V_m	$V_{r.v.}$
131	A	20	143	19	5.1	—	—
132	R	0	46	18	1.7	—	—
133	R	0	64	22	2.0	—	—
134	A	0	207	17	8.3	—	—
135	R	0	47	21	1.5	—	—
136	R	0	40	23	1.2	—	—
137	A	16	141	17	5.7	—	—
138	A	20	118	21	3.8	—	—
139	A	14	88	20	3.0	—	—
140	A	18	88	17	3.5	—	—
141	A	19	98	17	3.9	—	—
142	R	12	49	16	2.1	—	—
143	A	25	78	18	3.0	—	—
144	A	19	92	23	2.7	—	—
145	A	20	144	23	4.3	—	—
146	R	4	70	19	2.5	—	—
147	A	16	79	15	3.6	16	17
148	R	5	70	25	1.9	—	—
149	R	7	50	26	1.3	—	—
150	A	20	89	19	3.2	—	—
151	A	23	95	20	3.2	—	—
152	R	13	78	27	2.0	—	—
153	A	20	93	23	2.8	—	—
154	A	15	69	16	2.8	—	—
155	R	2	35	24	1.0	—	—
156	R	2	67	22	2.1	—	—
157	R	2	71	22	2.2	—	—
158	R	0	70	24	2.0	—	—
159	R	0	60	23	1.8	—	—
160	A	0	138	15	6.3	—	—
161	R	0	68	22	2.1	—	—
162	A	10	55	20	1.9	12	13
163	A	16	100	16	4.3	—	—
164	A	22	103	11	6.4	—	—
165	A	12	103	11	6.4	—	—
166	A	20	58	18	2.2	13	12
167	A	22	86	18	3.3	—	—
168	A	24	132	17	5.3	—	—
169	A	22	100	28	2.4	—	—
170	A	24	109	19	3.9	—	—
171	A	18	68	17	2.7	—	—
172	A	19	72	17	2.6	—	—
173	A	18	209	23	7.9	—	—
174	A	0	197	22	6.1	—	—
175	A	13	108	21	3.5	14	20

TABLE XXIX (Cont'd)

No.	Accept(A) or Reject (R)	Start of Merge V_m	G_f	$V_{r.v.}$	G_s	End of Merge V_m	$V_{r.v.}$
176	A	22	86	14	4.2	—	—
177	A	23	133	23	3.9	—	—
178	A	18	106	19	3.8	—	—
179	A	23	111	18	4.2	—	—
180	A	21	165	24	4.7	—	—
181	A	18	155	21	5.0	—	—
182	A	19	177	21	5.7	—	—
183	A	19	130	18	4.9	—	—
184	A	22	129	18	4.9	—	—
185	A	24	125	18	4.7	—	—
186	A	13	121	21	3.9	—	—
187	A	19	63	11	3.9	20	13
188	A	20	143	21	4.8	—	—
189	A	16	155	17	6.2	—	—
190	A	21	173	22	5.4	—	—
191	A	19	185	20	6.3	19	21
192	A	15	170	23	5.0	—	—
193	A	17	120	15	5.4	—	—
194	A	17	184	19	6.6	—	—
195	A	21	145	17	5.8	—	—
196	A	13	112	20	3.8	—	—
197	A	18	130	21	4.2	—	—
198	A	22	147	21	4.8	—	—
199	A	23	116	22	3.6	—	—
200	A	20	103	18	3.9	—	—
201	R	10	63	20	2.2	—	—
202	R	5	84	15	3.8	—	—
203	R	6	60	26	1.6	—	—
204	A	20	130	18	4.9	—	—
205	A	25	122	24	3.5	—	—
206	A	21	123	18	4.7	—	—

TABLE XXX

Gap Observations — Whitehead Highway and Circle Daylight Study

No.	*Accept(A) or Reject (R)*	*Start of Merge* V_m	G_f	$V_{r.v.}$	G_s	*End of Merge* V_m	$V_{r.v.}$
1	A	19	57	20	1.9	17	19
2	A	8	93	17	3.7	—	—
3	R	19	41	21	1.3	—	—
4	A	15	70	21	2.3	—	—
5	A	19	110	14	5.4	—	—
6	A	21	108	22	3.2	—	—
7	R	20	66	20	2.3	—	—
8	A	19	65	14	3.2	—	—
9	A	19	99	23	2.9	—	—
10	A	19	63	18	2.4	—	—
11	R	18	84	19	3.0	—	—
12	A	16	81	19	2.9	—	—
13	A	22	106	17	4.3	21	18
14	A	23	53	16	2.3	23	18
15	A	22	104	12	5.9	—	—
16	A	24	41	14	2.0	24	13
17	A	21	40	10	2.7	15	13
18	A	18	71	16	3.0	—	—
19	A	17	129	16	5.5	18	19
20	A	12	53	19	1.9	15	14
21	A	23	121	21	3.9	—	—
22	A	19	46	14	2.2	14	12
23	A	13	115	19	4.1	13	19
24	A	21	54	16	2.3	—	—
25	A	23	70	18	2.7	—	—
26	A	21	61	15	2.8	—	—
27	A	22	77	19	2.8	—	—
28	A	19	75	18	2.8	—	—
29	A	16	48	16	2.1	16	17
30	A	15	51	14	2.5	—	—
31	A	19	121	22	3.8	—	—
32	A	20	89	16	3.8	—	—
33	A	11	91	17	3.7	—	—
34	A	17	55	16	2.3	—	—
35	A	25	119	16	5.1	—	—
36	A	20	87	23	2.6	—	—
37	R	18	35	14	1.7	—	—
38	A	17	46	13	2.4	11	10
39	A	14	54	18	2.0	15	17
40	A	16	81	18	3.1	—	—
41	R	27	34	24	1.0	—	—
42	A	20	104	26	2.7	—	—
43	A	17	50	11	3.1	—	—
44	A	11	44	12	2.5	—	—
45	A	18	124	22	3.8	—	—
46	A	14	63	11	3.9	—	—
47	A	20	57	20	1.9	—	—
48	A	14	67	19	2.4	—	—
49	A	25	97	18	3.7	—	—

TABLE XXXI

Gap Observations — Wells Street and Circle Night Study

No.	Accept(A) or Reject (R)	Start of Merge V_m	G_f	$V_{r.v.}$	G_t	End of Merge V_m	$V_{r.v.}$
1	A	22	132	20	4.5	—	—
2	A	20	81	16	3.4	—	—
3	R	15	60	23	1.8	—	—
4	R	3	53	22	1.6	—	—
5	R	0	57	16	2.4	—	—
6	R	1	69	20	2.4	—	—
7	R	2	100	23	3.0	—	—
8	A	2	187	23	5.5	—	—
9	A	17	218	20	7.4	—	—
10	A	20	106	20	3.6	—	—
11	A	23	107	20	3.6	—	—
12	A	15	116	21	3.8	—	—
13	A	22	133	21	4.3	—	—
14	A	21	133	17	5.3	—	—
15	R	10	78	24	2.2	—	—
16	R	2	132	23	3.9	—	—
17	A	18	144	25	3.9	—	—
18	A	9	84	21	2.7	15	21
19	R	13	50	21	1.6	—	—
20	R	6	72	24	2.0	—	—
21	R	1	129	22	4.0	—	—
22	R	0	83	22	2.6	—	—
23	R	0	114	20	3.9	—	—
24	R	0	59	23	1.7	—	—
25	R	0	94	13	4.9	—	—
26	R	0	63	24	1.8	—	—
27	A	0	114	13	6.0	—	—
28	R	1	72	17	2.9	—	—
29	R	3	114	22	3.5	—	—
30	A	14	154	19	5.5	—	—
31	A	22	208	26	5.4	—	—
32	A	22	100	17	4.0	—	—
33	R	12	98	19	3.5	—	—
34	A	17	103	12	5.9	—	—
35	A	21	99	21	3.2	—	—
36	A	21	102	23	3.0	—	—
37	A	23	130	19	4.7	—	—
38	A	21	75	17	3.0	23	19
39	R	4	76	19	2.7	—	—
40	R	2	96	16	4.1	—	—
41	A	0	120	15	5.4	—	—
42	A	12	37	13	1.9	17	15
43	R	2	79	21	2.6	—	—
44	R	2	85	19	3.1	—	—
45	R	1	96	22	3.0	—	—

TABLE XXXI (Cont'd)

No.	Accept(A) or Reject (R)	Start of Merge				End of Merge	
		V_m	G_f	$V_{r.v.}$	G_s	V_m	$V_{r.v.}$
46	R	2	84	20	2.9	—	—
47	R	1	63	22	2.0	—	—
48	R	0	112	24	3.2	—	—
49	R	0	112	24	3.2	—	—
50	A	19	124	23	3.7	—	—
51	A	22	195	17	7.8	—	—
52	R	12	38	21	1.2	—	—
53	R	2	96	20	3.3	—	—
54	R	2	54	21	1.8	—	—
55	A	11	175	16	7.5	—	—
56	A	20	122	18	4.6	—	—
57	A	11	117	27	3.0	11	13
58	A	23	84	16	3.6	—	—
59	R	13	65	21	2.1	—	—
60	A	20	128	20	4.4	—	—
61	R	12	44	18	1.7	—	—
62	A	14	103	20	3.5	—	—
63	A	13	69	16	2.9	17	18
64	A	20	154	21	5.0	—	—
65	A	18	51	17	2.0	17	18
66	A	15	53	16	2.3	14	14
67	A	20	110	17	4.4	—	—
68	R	7	37	24	1.0	—	—
69	R	10	66	24	1.9	—	—
70	R	13	53	24	1.5	—	—
71	R	1	82	21	2.7	—	—
72	R	3	81	21	2.6	—	—
73	R	8	92	18	3.5	—	—
74	R	1	100	19	3.6	—	—
75	A	26	70	18	2.7	—	—
76	R	2	65	23	1.9	—	—
77	A	19	139	15	6.3	—	—
78	A	18	117	19	4.2	—	—
79	A	18	140	21	4.5	—	—
80	A	18	172	16	7.3	—	—
81	A	20	72	18	2.7	20	18
82	A	16	153	13	8.0	—	—
83	R	5	59	18	2.2	—	—
84	A	17	68	8	5.8	—	—
85	R	8	42	16	1.8	—	—
86	R	0	69	27	1.7	—	—
87	A	19	109	18	4.1	—	—
88	A	17	108	19	3.9	—	—
89	A	15	129	21	4.2	—	—
90	R	1	102	26	2.7	—	—

TABLE XXXII

Gap Observations — Combined Two-Car Gaps

No.	Accept(A) or Reject (R)	Start of Merge V_m	G_f	$V_{r.v.}$	G_t	End of Merge V_m	$V_{r.v.}$
1	A	13	225	11	13.9	—	—
2	A	19	140	17	5.6	18	15
3	A	15	95	18	3.6	17	16
4	A	18	163	21	5.3	18	19
5	A	14	96	18	3.6	15	13
6	A	16	141	17	5.7	—	—
7	R	20	118	21	3.8	—	—
8	A	16	155	17	6.2	—	—
9	A	22	195	17	7.8	—	—
10	A	14	154	19	5.5	—	—
11	A	16	153	13	8.0	—	—
12	A	22	106	17	4.3	21	18
13	A	17	129	16	5.5	19	19
14	A	13	115	19	4.1	13	19

TABLE XXXIII

Gap Data Computed from Wynn's Weaving Study

No.	Start of Weave				End of Weave	
	V_m	G_f	$V_{r.v.}$	G_s	V_m	$V_{r.v.}$
123	39	54	36	1.0	35	35
188	38	57	32	1.2	39	35
197	38	57	39	1.0	36	36
167	33	56	34	1.1	29	29
148	32	56	36	1.1	35	36
105	41	74	37	1.4	36	33
158	41	73	38	1.3	17	23
186	25	53	28	1.3	28	27.5
201	32	65	28	1.6	26.5	25
134	39	76	40	1.3	36	35
118	34	70	40	1.2	31	30
113	41	82	40	1.4	40	35
149	35.5	82	35	1.6	35.5	34
151	29	67	28	1.6	25	26
154	32	79	35	1.5	22	22
150	39	92	30	2.1	35	28
138	43	98	40	1.7	40	35
128	25	68	28	1.7	25	24
146	38	96	39	1.7	31	32
114	40	104	40	1.8	35	38
131	38	102	40	1.7	33	35
129	21	70	23	2.1	25	23
145	30	110	39	1.9	30	35
102	34	152	42	2.5	34	42