ANNOTATED BIBLIOGRAPHY ON GAP ACCEPTANCE AND ITS APPLICATIONS

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CONTENTS

A. GAP ACCEPTANCE

1. Gourlay, S. M., "Merging Traffic Characteristics Applied to Acceleration Lane Design," A Thesis submitted to the Bureau of Highway Traffic, Yale University, 1946.

The problem investigated in this study involved 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.

2. Strickland, R. I., "A Study of Merging Vehicular Traffic Movements," A Thesis submitted to the Bureau of Highway Traffic, Yale University, 1947.

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

3. Greenshields, B. D., Schapiro, D., Ericksen, E. L., Traffic Performance at Urban Street Intersections, Yale University, New Haven, Conn., 1947.

The intersection of streets at grade in urban areas is a primary location of traffic accidents and source of congestion. One-half of all urban traffic accidents and more than three-fourths of all delays experienced in dense urban areas are related to intersections. In order to cope successfully with these problems the traffic engineer should fully understand the phenomena of merging, crossing and diverging vehicular movements which make up the intersectional traffic stream.

It is essential, therefore, to analyze the time-space relationships which occur between the various units in the traffic stream; upon these kinships must rest the solution to the problems of intersection operation.

The study involves a preliminary exploration into fundamental relationships which exist between traffic units. Acceleration and deceleration characteristics are considered as are methods of applying the knowledge to traffic behavior at non-controlled intersections. The applicability of the Poisson Theory to vehicular traffic patterns is demonstrated.

4. Raff, M.S., and Hart, J.W., "A Volume Warrant for Urban Stop Signs," Saugatuck, Conn., The Eno Foundation for Highway Traffic Control, 1950.

5. Tanner, J.C., "The Delay to Pedestrians Crossing a Road," Biometrika, 38:3 and 4, Dec. 1951.

Delay to pedestrians waiting to cross a road depends upon the availability of a sufficient gap in the traffic. If reasonable assumptions are made concerning his behavior and that of the traffic, the expected may be quantified.

If the traffic arrivals follow the Poisson distribution and pedestrians arrive at the crossing point at some rate per given time (randomly and independent of vehicular passages), a mathematical solution for delay is possible. This relationship is based upon some gap, T, which could be considered "sufficient" for crossing and can account for individual pedestrians or the frequent groups of two or more pedestrians.

6. Mayne, A.J., "Some Further Results in the Theory of Pedestrians and Road Traffic," Biometrika, Vol. 41, 1954.

Tanner (1951) has considered several statistical problems about the passage of pedestrians across a road, on the assumption that vehicles and pedestrians arrive at random. Here, his main results are generalized to the case where the time intervals between successive arrivals have a given distribution, any two such intervals being independently distributed. Tanner's results follow for the special case when the interval distributions are negative exponential, which occurs when there is a random flow of traffic. The size of groups of pedestrians on an island between two lanes of traffic is also considered. The effect of the presence of islands on pedestrian delay is discussed, and it is shown that, under certain conditions, the 'efficiency' in two specially

defined senses can be multiplied by at least r^2, by the introduction of (r-1) islands suitably spaced in the middle of the road. Finally, the results are given of a further examination of some empirical traffic data, which supplements the work of Adams (1936-1948).

7. Bissell, H. H., "Traffic Gap Acceptance from a Stop Sign," Graduate Research Report (unpublished), Institute of Transportation and Traffic Engineering, University of California, Berkeley, 1960.

8. Little, J. D. C., "Approximate Expected Delays for Several Maneuvers by a Driver in Poisson Traffic," Operations Research, 9:1, Jan.-Feb., 1961.

Models are given for calculating the expected delay to a driver in making several maneuvers at or near a traffic light. These include going straight through, turning left, and various entrances and exits from the traffic stream. Traffic approaching the intersection is assumed to be Poisson. Approximations are used that apply at medium and low traffic flows.

9. Herman, R. and Weiss, G., "Comments on the Highway Crossing Problem," Operations Research 9:6, Nov.-Dec. 1961.

A discussion is given of the gap acceptance problem confronting a driver at a stop sign who is attempting to cross a single lane of traffic. This problem is discussed in the light of a gap acceptance probability that is taken in the form: $a(t)=0$ when $t<T$ and $1-a(t)=\exp -\lambda (t-T)$ when $t>T$, rather than a step function as has been considered in the past. Some experimental information is discussed concerning the values of the parameters and T in such situations. This information coupled with theoretical considerations allows one to estimate quantities such as mean delay time, probability of zero delay, and highway transparency. Comments are made concerning the influence of car performance on road crossing and on entering highways.

10. Weiss, G. and Maradudin, A., "Some Problems in Traffic Delay," Operations Research 10:1, Jan-Feb., 1962.

The problems that are considered here concern the delay to a single car waiting at a stop sign for a sufficiently large gap in the oncoming traffic to present itself so that the driver considers it safe to cross the highway. The systematic application of renewal theory techniques offers a method of solving these problems, which is much simpler than the combinatorial solutions published by TANNER and MAYNE in the treatment of somewhat simpler versions. It is assumed

that successive gaps in the main highway traffic are uncorrelated random variables with known probability density. They treat the probability of crossing the highway as a known function, a(t), rather than a step function. It is shown that the distribution of delay times satisfies a convolution integral equation, and that the moments are easily found using Laplace transforms. Integral equations are also found for the delay distribution when the gap distribution is non-stationary, e. g., when traffic light effects are important. Finally the case of semi-Markov correlated gaps are considered, and a formal expression for the delay distribution is given.

11. Blunden, W. R., C. M. Clissold, R. B. Fisher, "Distribution of Acceptance Gaps for Crossings and Turning Maneuvers," Australian Road Research Board Proceedings, Vol. 1, 1962.

This paper describes studies that have been made on the distributions of the gaps required by drivers to turn into and cross a free-flowing traffic stream. Attention has been focused on the driver-vehicle parameter and the type of maneuver, and it was sought, where possible, to regard the other variables as boundary conditions. However, the fact that field measurements were carried out at a number of different locations at different times permitted some spot checks to be made on the effect of environmental parameters (flow in main stream, speed of entering vehicles, commercial vehicle percentage) on the gap distribution. A theoretical distribution has been fitted to the experimental data for left-turn merging maneuvers and a formula for the delay resulting from the distribution of gaps has been developed and compared with measured delays.

12. Major, N. G. and Buckley, D. J., "Entry to a Traffic Stream," Australian Road Research Board Proceedings, Vol. I, 1962.

An investigation has been made into the process of traffic entering a passing traffic stream under certain conditions in order to assess the relative merits of single and multiple entry points. Expressions for the mean delay to entering vehicles have been obtained and are found to agree well with field data. These expressions, together with certain earlier expressions for absorption rates, have been extended to more than one entry point and certain conclusions reached. The effect of entering traffic upon the characteristics of a traffic stream have been investigated, and procedures and conditions relevant to the application of the results are outlined.

13. Tanner, J. C., "A Theoretical Analysis of Delays at an Uncontrolled Intersection," Biometrica, 49:1 and 2, 1962.

The problem dealt with is delay to minor stream traffic at uncontrolled intersections where major street traffic has the right of way. It was assumed that major stream arrivals were random and no closer than some time, in the mathematical development. Likewise, minor stream traffic is random and will not enter (pass through) the major stream in intervals less than some duration of time. The third assumption is that there is some minimum time following the passing of a major stream vehicle before the minor stream vehicle will execute his maneuver.

A model was derived for the average delay to minor stream traffic when the system is in static equilibrium. The results are compared with expected delays at signals.

14. Haight, F. A., E. F. Bisbee, and C. Wojcki, "Some Mathematical Aspects of the Problem of Merging," Highway Research Board Bulletin No. 356, 1962.

This publication does not claim a complete mathematical model for merging, but it points out some of the problems in the formulation of such a model, and solves a few of them. From the purely mathematical point of view, the merging problem has some interest beyond the simple question of waiting for a suitable gap in traffic. It might be supposed, for example, that a car traveling along an acceleration lane while waiting for the opportunity to merge is mathematically equivalent to a car waiting at a stop sign, or that the difference resides only in the moving coordinate system. However, the driver on the acceleration lane is able to control the traffic stream with which he wishes to merge by changing his own speed, thereby increasing or decreasing his headway and spacing relative to the main stream. The stop sign problem does not contain this important ingredient, and therefore questions of driving policy do not arise. There is only one possible policy at a stop sign: wait for a suitable gap. Therefore, a mathematical model for a stop sign is purely descriptive, and its principal result consists of a probability distribution for delay.

15. Evans, D. H., Herman, R. and Weiss, G. H., "The Highway Merging and Queueing Problem," Operations Research, 12:6, Nov.-Dec. 1964.

This paper presents a study of several aspects of the theory of car queues. In it is considered a situation in which there is traffic on a

main highway and a queue of cars on a side road waiting to merge. The first considerations is the case in which the lead driver chooses to merge on the basis of whether the gap in the main stream exceeds a service time that is chosen from a probability density. An expression for the generating function of the steady-state distribution and the wait-time distribution are derived. Secondly, the critical input to the side road is determined such that for all larger inputs the queue is transient. In particular consideration is given to the effect of the move-up time of the second car in the queue on this parameter. Finally, results are obtained by simulation for the analysis of traffic queueing models, then compared with theoretical results.

16. Jewell, W. S., "Forced Merging in Traffic," Operations Research, 12:6, Nov.-Dec., 1964.

A vehicle waiting at an intersection with a major road makes a merging maneuver into the mainstream traffic, thus possibly requiring oncoming traffic to slow down. This report examines the resulting disturbance that this forced entry may create in the mainstream, assumed to be a renewal process. After showing that the disturbance propagation is formally equivalent to the busy period of a related queueing model, explicit results on the length of disturbance period and the number of vehicles affected are obtained for the case of Poisson Traffic. It is shown that there is some minimal mainstream headway which should be forced in order to maximize the rate at which entries can be made from the secondary road. Finally, two measures of accident potential for the merging maneuver are presented.

17. Solberg and Oppenlander, J. C., "Lag and Gap Acceptances at Stop-Controlled Intersections," Highway Research Record No. 118, 1965.

The purpose of this research study was to investigate the lag and gap acceptance for drivers entering and crossing a major roadway from a stopped position. This driver-behavior evaluation included a determination of a lag and gap acceptance distribution for the side-street drivers, consideration of community influence on this distribution, and comparisons of time-interval acceptances by drivers making through, left-turn, and right-turn movements.

The study was performed at right-angle intersections formed by two-way, two-lane, urban streets. Four sites, selected in Lafayette and Indianapolis, Ind. were as possible regarding geometry and adjacent land use. The data were collected at these sites by means of a motion picture camera. The technique of probit analysis was employed

in the statistical treatment of the observations. In addition, two other methods, one developed by Raff and the other by Bissell, were considered in this evaluation of driver behavior at stop-controlled intersections.

The acceptance distributions were well described by a linear relationship between the probit of acceptance and the logarithm of acceptance time. There were no significant difference between the median lag-acceptance and the median gap-acceptance times at the four intersections. However, significant variations were found between right- and left-turning drivers and between drivers proceeding through the intersection and those making left turns. Right-turning drivers and those crossing the intersection had statistically equal median acceptance times. Community size apparently has some influence on driver performance at intersection approaches controlled by stop signs. A general agreement existed among the three methods of analysis investigated.

18. Wagner, A., Jr., "An Evaluation of Fundamental Driver Decisions and Reactions at an Intersection," Highway Research Record No. 118, 1965.

This paper reports the field measurement and analysis of fundamental driver decision and reaction parameters at a stop-signed intersection. The following research objectives were pursued:

1. A detailed examination to determine and verify the characteristics of lag and gap acceptance of drivers waiting at a stop sign.
2. Evaluation of the influence of the following traffic factors on driver decisions: (a) vehicle type, (b) pressure of traffic demand, (c) direction of movements through the intersection, (d) sequence of gap formation, and (e) conditions on the opposing side street approach.
3. Determination of the characteristics of starting delay time in accepting lags and gaps, and evaluation of the influence of certain traffic factors on these distributions.

The results strongly supported earlier findings which indicated the relationship between lag or gap size and percent acceptance is log-normal. Of the traffic factors studied, those which significantly influenced driver decisions were (a) pressure of traffic demand, (b) direction of traffic movement during periods of heavy demand, and (c) sequence of gap formation during periods of heavy demand.

Definitions of starting delay time in accepting lags and gaps were set forth. Analysis of field observations of this parameter indicated

that factors which had important influence on driver decisions, namely, pressure of traffic demand and sequence of gap formation, had similar and significant effects on starting delay times.

19. Drew, D. R., "Gap Acceptance Characteristics for Ramp-Freeway Surveillance and Control," Presented at the Annual Meeting of the Highway Research Board, Washington, D. C., Jan. 1966.

An investigation was made to determine gap acceptance characteristics and merging delay characteristics for six inbound entrance ramps on the Gulf Freeway in Houston. A 20-pen graphic recorder operated by four men stationed adjacent to the merging area between the freeway and the frontage road was used in collecting the data.

Merging vehicles were divided into two groups--those in which the driver rejected gaps before finally accepting a gap and those in which the driver of a ramp vehicle accepted the first gap. The former was referred to as "stopped" vehicles and the latter "moving vehicles." The critical gap for stopped vehicles was found to be about 20 percent higher than for moving vehicles. In addition, it was concluded that the critical gap (median) for the merging maneuver from an entrance ramp is independent of the freeway volume but is apparently affected by ramp geometrics and ramp controls.

A distribution of critical gaps was formed and fitted to a gamma distribution. Merging delay values calculated using this distribution were shown to be higher than those calculated assuming that all drivers have the same fixed critical gap. The calculated values were also compared to observed merging delays.

20. Weiss, G. H., "The Intersection Delay Problem with Correlated Gap Acceptance," Operations Research 14:4, July-Aug., 1966.

This paper considers a modification of the single car intersection delay problem in which the waiting driver, upon finding a suitable gap for crossing also examines the succeeding one, and uses it if it is larger. It is shown that the additional delay time caused by this method of gap acceptance is generally quite small.

21. Desrosiers, R. D., "Gap Utilization - A Warrant for Traffic Signal Control." Traffic Engineering, Vol. 37:3, Dec, 1966.

A highway traffic signal is a means of allocating time and space to conflicting movements at intersections. A logical approach to warrant signalization is gap utilization, or the probability of a gap on a

major stream being greater than the "critical" gap of a minor stream vehicle. The hypothesis is that the number of minor stream vehicles that can be accommodated by the main stream is based on gap utilization. If this number exceeds the demand of the minor stream, no signalization is required. The theory can account for any number of maneuvers and is applicable to any unsignalized intersection.

22. Drew, D. R., LaMotte, L. R., Buhr, J. H. and Wattleworth, J. A., "Gap Acceptance in the Freeway Merging Process," Texas Transportation Institute Research Report 430-2, College Station, Texas, Dec. 1966.

The theoretical development of models and useful parameters for describing the merging process include (1) the derivation of the forms of the mean and variance of the delay to a ramp vehicle in position to merge and (2) the treatment of the variability of critical gaps and gap acceptance among drivers through the identification of the representative forms for both critical gap distributions and gap acceptance functions.

Through the application of "individual record probit analysis;" simple, statistically significant relations between the percent gap acceptance and gap size is established. Using this approach, the characteristics of lags and gaps and single and multiple entry merges are compared, as well as fast to slow moving merging vehicles. The probit analyses are generalized to establish a relationship between percent acceptance as the dependent variable and gap size and vehicular speed as the dependent variables.

Data were collected at 32 entrance ramps across the United States, selected to reflect diverse operating, geometric, geographic and environmental conditions. Enough data was collected to run 1344 usable gap acceptance regressions.

B. TRAFFIC QUEUEING THEORY

1. Tanner, J.C., "A Problem of Interference Between Two Queues." Biometrika, Vol. 40, June, 1953.

This paper is concerned with the delays that occur when two opposing streams of vehicles are trying to pass along a length of road only wide enough for one vehicle at a time. The problem is treated theoretically. It is noted that the mathematical difficulties were found to be very great, and the problem as first formulated has not been completely solved. The results obtained have applications to several other road traffic problems, such as delays to pedestrians crossing a road, delays to vehicles at uncontrolled intersections, and delays to intersecting streams of pedestrians.

2. Doig, A., "A Bibliography on the Theory of Queues." Biometrika, 44, Dec., 1957.

This bibliography lists papers on those aspects of the theory of probability which may be grouped together under the heading of the study of queues. References are given both to purely theoretical work and to the practical applications of the subject, including its application to the study of traffic.

3. Newell, G.F., "The Flow of Highway Traffic Through a Sequence of Synchronized Traffic Signals." Operations Research, Vol. 8, No. 3, May-June, 1960.

4. Newell, G.F., "Queues for a Fixed-Cycle Traffic Light." Annals of Mathematical Statist. Vol. 31, No. 3, Sept. 1960.

The steady-state behavior of an automobile queue, with Poisson arrivals and with a cyclic red-green traffic light, is calculated. Analytic expressions for the average queue length and the average delay are obtained. The results are compared with those of earlier work on the same subject.

5. Little, J.D.C., "Approximate Expected Delays for Several Maneuvers by Driver in Poisson Traffic." Operations Research Vol. 9, No. 1, Jan.-Feb. 1961.

Models for calculating expected delay to a driver in making several maneuvers at or near traffic light, which include going straight through, turning left, and various entrances and exits from traffic

stream; traffic approaching intersection is assumed to be Poisson type; approximations are used that apply at medium and low traffic flows.

6. Herman, R., Weiss, G., "Comments on the Highway-Crossing Problem." Operations Research, Vol. 9, No. 6, 1961.

The crossing problem in question is to calculate the waiting time before a sufficiently large gap appears in a traffic stream for a pedestrian or driver to cross the stream. Previous studies have dealt with the case where one waits for a gap of length T or more. The present study considers the more general case in which there is a probability $\alpha(t)$ that one accepts a gap of length t. Experimental data relating to the form of $\alpha(t)$ are presented, also calculations and graphs when $\alpha(t)=0$ for $t<T$ and $1 - \alpha(t)$ is exponential for $t>T$.

7. Weiss, G. H., and Maradudin, A. A., "Some Problems in Traffic Delay." Operations Research, Vol. 10, No. 1, Jan.-Feb., 1962.

The problems that are considered here concern the delay to a single car waiting at a stop sign for a sufficiently large gap in the oncoming traffic to present itself so that the driver considers it safe to cross the highway. The systematic application of renewal theory techniques offers a method of solving these problems. It is much simpler than the combinatorial solutions published by Tanner and Mayne in the treatment of somewhat simpler versions. It is assumed that successive gaps in the main highway traffic are uncorrelated random variables with known probability density. We treat the case that the probability of crossing the highway is a known function, $\alpha(t)$, rather than a step function. It is shown that the distribution of delay times satisfies a convolution integral equation, and that the moments are easily found using Laplace transforms. Integral equations are also found for the delay distribution when the gap distribution is non-stationary, e.g., when traffic light effects are important. Finally the case of semi-Markov correlated gaps are considered, and a formal expression for the delay distribution is given.

8. Dorfwirth, J.R., "Delay and Queueing of Motor Vehicles at Uncontrolled Intersections." Neue Folge, Heft 43: Bad Godesberg, (In German), 1961.

The theory of stochastic processes is applied to the problem of calculating the capacity of uncontrolled road intersections and the time lost in queues.

9. Miller, A. J., "A Queueing Model for Road Traffic Flow." Journal Royal Statistical Society Series B Vol. 23, No. 1, 1961.

Author's summary: "It is proposed that on roads which are uninterrupted by traffic signals, intersections, etc., vehicles should be considered as travelling in random queues. Criteria for determining the queues in actual traffic are found. A crude model is then used to study the formation of these queues in an attempt to derive the Borel-Tanner distribution of queue lengths. The random queues model is then used to study waiting times for pedestrians (or vehicles) wishing to cross one lane of traffic."

10. Hammersley, J. M., "The Mathematical Analysis of Traffic Congestion." (French Summary) Bulletin of the Institute of International Statistics 39, livraison 4, 1962.

11. Blunden, W. R., "On the Theory of Traffic Flow." Proceedings of the Australian Road Research Board, Vol. 1, Pt. 1, 1962.

A generalized concept of non-programmed traffic flow based on a queueing model is described. The interaction between the input to a traffic facility (i. e., demand for service, volume) and its inherent flow capability (i. e., saturation flow rate or capacity) gives rise to delay--the principal measure of performance of the facility. The saturation flow rate is derived from the distribution of service times arising from multi-variant population of drivers, vehicles and/or traffic facilities. Data are given on saturation flow rates to toll gates, bus stops, intersections, retailing channels and air strips. Discussion is included on the stability of traffic flow, its operating efficiency under varying traffic loads and the principles underlying the analysis and synthesis of flow in traffic networks.

12. Kingman, J. F. C., "On Queues in Heavy Traffic," Journal Royal Statistical Society Series B, Vol. 24, No. 2, 1962.

Queueing theory, which has endured a long period in which people treated one example after another, is finally breaking out of its confinement to independent arrivals, service times, etc. The present paper represents a significant step in that direction. The author considers a single-server queue in heavy traffic, i. e., traffic intensity close to 1, or more properly a small value of $\alpha = -E(u)/Var(u)$, where u is the difference between the service times and the interarrival times chosen here to be stationary but not necessarily independent. The object is to show that for $\alpha \to 0$, the waiting times α typically has a limit distribution which is exponential with mean 1/2. This is proved first

for independent arrivals and service times with mild restrictions on their distributions and then extended to a class of inputs for which the arrivals differ from a renewal process by (dependent) random variables dominated by one with a finite second moment. The results are shown to be applicable to tandem queues and scheduled arrivals. In fact, the theorems, or rather obvious extensions of them, can be made to apply to most of the common queueing type problems where one is sufficiently close to the critical intensity.

13. Kisi, T., Hiyoshi, K., "The Effect of a Traffic Light on a Poisson Flow." Journal of the Operations Research Society of Japan, Vol. 6, 1962-63.

At a sufficiently large distance from a traffic light, the distribution of cars should approach a Poisson distribution. The authors describe a simple theory for this and compare it with experimental results.

14. Passau, P., "Delays Incurred by Vehicles Stopped at Traffic Lights." International Road Safety Traffic Review, 11 (3), 1963.

It is assumed that the time intervals between vehicles arriving at traffic signals are exponentially distributed and that the departure times depend linearly on the position in the queue. Formulae are given for the average delay in relation to the length of the red period. The results can be used to determine the optimum setting of fixed phase lights.

15. Darroch, J.N., "On the Traffic-Light Queue." Annals of Mathematical Statistics, Vol. 35, No. 1, March 1964.

A formal solution for the stationary distribution of queue-length at a fixed-cycle traffic light is found for a fairly general distribution of arrivals and for a single stream of vehicles which either all turn left or else all go straight on or turn right. Some equations are derived for the expected queue-length and for the expected delay per vehicle.

16. Queueing Theory Approaches. Highway Research Board-Special Report 79, 1964.

This report presents the results of studies of probability models of traffic delay; characteristics governing arrival of streams of traffic at a given point and variability of gap acceptance of drivers and pedestrians attempting to cross a traffic stream; summaries of elements of queueing or waiting-line theory, and publications relative

to delays at signalized and stop-sign controlled intersections, multiple queues, parking and single lane bottlenecks. 76 references are given.

17. Evans, D. H., and Herman, R., "The Highway Merging and Queuing Problem." Operations Research, Special Transportation Science Issue, Vol. 12, No. 4, Nov.-Dec. 1964.

A study of several aspects of the theory of car queues is presented. A situation is considered in which there is traffic on a main highway and a queue of cars on a side road waiting to merge. A case is discussed in which the lead driver chooses to merge on the basis of whether the gap in the main highway traffic exceeds a service time chosen from a probability density. An expression for the generating function of the steady-state distribution and the waiting-time distribution is derived. The critical input to the side road is determined such that for all larger inputs the queue is transient. In particular, the effect of the move-up time (of the second car in a que) on this parameter is considered. Results are presented of a study by simulation techniques for the analysis of traffic queuing models. A discussion of the use of importance sampling in improving simulation studies is given, and theoretical and simulation results are compared.

18. Kleinecke, D. C., "Discrete Time Queues at a Periodic Traffic Light." Operations Research, Special Transportation Science Issue, Vol. 12, No. 4, Nov.-Dec. 1964.

The response delay in clearing the queue of automobiles waiting at a traffic light can be modeled by allowing one car to leave at the end of each of a series of discrete intervals in time. The steady-state queue formed at a cycle traffic light is discussed for general stationary arrival processes. A method of solution for the case where arrivals are Poisson is described. General formulas are given for the probability of not clearing the queue during a cycle and for the expected wait at the light.

C. ENTRANCE RAMP OPERATION

1. Fukutome, Ichiro, Moskowitz, Karl, "Traffic Behavior and On-Ramp Design," Highway Research Board Bulletin 235, 1960.

Three ramp terminal designs were painted successively at one on-ramp location. Speed and placement of vehicles were recorded and movies were taken during each phase. Findings include the following:

1. All three designs resulted in similar vehicle paths, because essentially they were all liberal designs and traffic was able to drive a natural path.

2. Somewhat more length was used at low volumes than at high volumes, except during the 8-ft offset 50:1 taper phase, where the length used was approximately constant for all volumes.

3. The natural path of nearly all vehicles is contained within a 50:1 taper, and this design provides sufficient acceleration distance for all turning speeds.

It is concluded that ramp terminal design should be standardized and a tentative standard is offered together with supporting data and reasoning.

2. Pinnell, C., "Driver Requirements in Freeway Entrance Ramp Design," Texas Transportation Institute, Texas A&M University, December 1960.

The material presented is based upon the results of numerous freeway ramp studies conducted on freeways in Texas. Most of the data were obtained by motion picture studies. The studies produced much valuable information and resulted in the development of some new concepts of entrance ramp problems and operations.

Relating the design of freeway entrance ramps to traffic behavior as indicated by the requirements and desires of the driver is a necessity if maximum efficiency and safety in ramp and freeway operation is to be obtained. Entrance ramp design should provide flat angle ramp approach which aligns the driver along an easy and natural path into the freeway,, adequate visibility to allow entrance ramp driver to judge and accept a freeway gap with a minimum of effort, and a clearly marked and delineated entrance ramp which would eliminate any confusion in distinguishing between the entrance ramp elements and

the main freeway lanes.

A suggested standard design is offered.

3. Keese, C. J., Pinnell, C., McCasland, W. R., "A Study of Freeway Traffic Operation," Highway Research Board, Bulletin 235, 1962.

This paper reports on a research study, the objective of which was to correlate freeway operational characteristics with design features. Data were collected principally by the motion picture method.

Research was conducted on: operation and capacity, freeway volume control, lane use and placement, entrance ramps, and weaving. The results of these various studies indicate that the factors having the greatest effect on freeway operation are the design and operation of ramps and interchanges. The volume control, weaving, and entrance ramp studies produced some significant results which are discussed in the report and will contribute to the over-all knowledge of freeway operation.

4. Jouzy, N. C., Michael, H. L., "Use and Design of Acceleration and Deceleration Lanes in Indiana," Highway Research Record, No. 9, 1963.

The speed and lateral placement of vehicles on various designs of the acceleration and deceleration lanes of the Indiana Toll Road and the Interstate System of the State of Indiana were studied. Data on speeds and lateral placement of traffic using the acceleration and deceleration lanes were obtained by use of a motion picture technique. Spot speeds of through lane traffic were measured using an electromatic radar speed meter.

The study revealed that a large number of the driving public do not use acceleration and deceleration lanes properly. Acceleration or deceleration lane traffic was found to have little effect on the speed of the through lanes. The long direct taper type of design was found superior for both acceleration and deceleration lanes.

5. Hess, J. W., "Capacities and Characteristics of Ramp-Freeway Connection," Highway Research Record, No. 27, 1963.

This report presents some of the initial findings of a nationwide freeway ramp capacity study, for which data were gathered in 1960 and 1961. The capacities associated with ramp-freeway connections are described. Before merging capacities can be computed, the freeway

lane volume distribution must be known so that lane 1 (i.e. the shoulder lane) volume can be estimated for the given freeway volume. These percentage distributions for four-, six-, and eight-lane freeways are depicted by graphs. As an alternative method in estimating lane 1 volume, equations are presented for use when certain upstream and downstream adjacent ramp conditions exist. These equations make possible an increase in the accuracy of the lane 1 volume calculation. Several of the equations are presented in nomograph form. Two formulas determined by regression analyses are presented for use in determining free-flow merge capacity at one-lane on-ramps.

6. Hess, J. W., "Ramp-Freeway Terminal Operations as Related to Freeway Lane Volume Distribution and Adjacent Ramp Influence," Highway Research Record No. 99, 1965.

This report is a continuation of the report "Capacities and Characteristics of Ramp-Freeway Connections," contained in Highway Research Record No. 27. It terminates the analysis of the data collected during the nationwide Freeway Ramp Capacity Study.

The emphasis in this report is on equations for determining traffic volumes in lane 1, the right-hand freeway lane, at merging and diverging sections along the freeway. The main premise is that if the lane 1 volume can be kept at an acceptable leve, the freeway as a whole will be operating at free-flow conditions. The equations take into account freeway volume, ramp volume, and traffic action on adjacent ramps which have an effect on the lane volume at the ramp under consideration. Seventeen nomographs, derived from the equations, are introduced to provide a fast graphical solution to design and operational problems.

Auxiliary lane usage between on-and off-ramps is discussed and a method of capacity analysis is illustrated with a sample problem. Finally, preliminary results are given of on-ramp vehicle, freeway lane usage studies made in Detroit on the 6-lane Edsel Ford Expressway.

7. Worrall, R. D., Drake, J. S., Buhr, J. H., Soltman, T. J., Berry, D. S., "Study of Operational Characteristics of Left-Hand Entrance and Exit Ramps on Urban Freeways," Highway Research Record, No. 99, 1965.

The paper essentially deals with left-hand exit ramps for freeways and is divided into three main sections: (a) a study of the general operating characteristics of left-and right-hand entrance ramps on urban freeways; (b) an analysis of traffic behavior along a 2-mile section of

urban freeway containing two internal diamond interchanges; and (c) a comparative study of the reported accident rates at a sample of right- and left-hand entrance and exit ramps.

Brief descriptions are given of study locations and study techniques, together with a discussion of major results. Conclusions are drawn concerning the operational efficiency, relative safety and general suitability of left-hand entrance and exit ramps for urban freeways under the type of site conditions existing in the Chicago area.

8. Worral, R.D., Coutts, D.W., Echterhoff-Hammerschmid, H., and Berry, D.S., "A Study of Merging Behavior at Freeway Entrance Ramps" Presented at the Highway Research Board Annual Meeting, Jan. 1966.

A description is given of a study of gap acceptance and merging behavior at freeway entrance ramps. The phenomenon of merging behavior is discussed in general terms, and a conceptual framework for the analysis of gap acceptance and rejection at a freeway entrance ramp is presented. A brief critical review of previous empirical and theoretical research work in the field is also made.

A series of empirical studies was conducted during the summer of 1965 at one left-hand and one right-hand entrance ramp in the Chicago area. Apart from being located on opposite sides of the traveled way, these two ramps had basically similar design characteristics. Included are empirical comparisons of alternative analytical techniques, a consideration of gap acceptance and merging behavior as both a dynamic and of the static phenomenon, an evaluation of critical gap size and gap structure, an analysis of the effect of relative merging speed on gap acceptance criteria, and a study of multiple vehicle merges. In each of these analyses, comparisons are also shown between the results obtained at left-hand and right-hand ramps.

A selected bibliography of reference materials on entrance ramp design and merging behavior, and a computerized analysis technique developed for handling large quantities of empirical data are presented.

9. Wattleworth, J.A., Buhr, J.H., Drew, D.R., and Gerig, F.A., Jr., "Operational Effects of Some Entrance Ramp Geometrics on Freeway Merging," Texas Transportation Institute Research Report 430-3, Dec. 1966.

The general objective of this study was to determine the effects of entrance ramp geometrics on traffic operation in the freeway merging

process. More specifically the objective was to study the effects of acceleration lane length, angle of convergence and ramp grade on entrance ramp operation. Most of the analyses presented in this report concentrate on the first two of these geometric variables.

Studies were conducted at many entrance ramps in order to include a fairly wide range of the geometric elements. Ramps studied were located in Houston, Los Angeles, San Francisco, Sacramento, Chicago, Detroit, and New York City. The acceleration lanes of the ramps studied ranged from 240 to 1500 feet in length and the convergence angles ranged from 1° to 14°. Data from 23 of these entrance ramps are presented in this report, showing the affects of geometrics on ramp speeds at various positions and on some aspects of gap acceptance behavior.

10. Drew, D. R., Buhr, J. H., and Whitson, R. H., "The Determination of Merging Capacity and Its Application to Freeway Design and Control," Texas Transportation Institute Research Report 430-4, Feb. 1967.

This paper presents an approach to the determination of the capacity and service volumes in ramp-freeway merging areas based on the critical gap concept and on the distribution of gaps in the freeway shoulder lane. The service volumes suggested are developed from considerations of the ramp junction as a queueing system. A level of service can then be provided such that a ramp vehicle has a certain probability of finding the merging area empty. Another measure of level of service is the delay suffered by ramp vehicles. This aspect is treated and charts presented for its determination.

The merging parameters involve the critical gap of the junction. This critical gap can be estimated from the geometrics of the ramp-freeway junction by a regression equation, developed through the study of a number of entrance facilities, which relates the critical gap to the length of acceleration lane and the angle of convergence. Relationships are also presented for estimating the entire gap acceptance characteristics from these two geometric features.

The paper proceeds to discuss the application of the developed merging parameters in freeway design and control.

D. FREEWAY TRAFFIC CONTROL

1. Forbes, T. W., and Gervais, Edward, "Effectiveness of Symbols for Lane Control Signals," Highway Research Board Bulletin, 244, Jan. 1959.

To test the readiness of understandability by the majority of motorists of signals for control of individual traffic lanes, research was carried out in two parts. Part 1 was an engineering psychology approach, which measured the types of meaning most commonly associated with six different possible symbols. A total of 253 graduate and undergraduate students viewed signal presentations by means of colored slides showing the signals as if in place on the Mackinac Bridge and gave a total of about 4,200 reactions to the critical signal.

Three experiments in Part 1 showed a consistent advantage for the "red X" as most often associated with the desired interpretation of "do not drive in this lane" or "move into another lane" and least often with the undesired "stop." The standard red bullseye, on the other hand, consistently showed a lesser proportion of the desired response and the largest proportion of "stop" responses. The laboratory study, therefore, confirmed the hypothesis that for most motorists the "red X" possessed advantageous natural associations with the desired meanings.

Part 2 consisted of checks of actual effects on bridge traffic of the "red X" and "green-arrow-up." A simple experimental setup employed a light wooden barrier and red flag in the righthand lane beyond the signals. The red X was turned on for this lane during every alternate 5-min period. Comparisons of the point at which the weave was started showed that motorists were responding to the red X signal.

Thus, the "red X" and "green-arrow-up" not only showed the advantage of natural association with a desired meaning as shown in the laboratory, but also produced the desired motorist reaction in actual traffic.

2. Barker, John L., "Determination of Discontinuities in Traffic Flow as a Factor in Freeway Operational Control." Traffic Engineering, Nov. 1961.

In the past, considerable study has been made of individual headways and speeds, and their relationship with respect to traffic lane production and performance. A number of theoretical formulae have

been developed to describe these relationships. This is a valid approach, but to produce an operational control system, a large amount of analysis of the individual characteristics of each vehicle is required. Conversely, considerable data has been collected on the gross production and performance of vehicle flow; this includes hourly volumes, daily volumes, speed distribution surveys, and other long term measurements of past happenings. These parameters, as such, are generally too coarse to be used for operational control.

3. Bushnell, K. and Richard, C., "The Development of Blankout Signals for Freeway Traffic Control." Presented at the International Municipal Signal Engineers Conference, Montreal, Canada, Sept. 1962.

4. Wattleworth, J.A., "Peak-Period Control of a Freeway System - Some Theoretical Considerations." Doctoral Dissertation, Northwestern University, August 1963.

5. "Ramp Metering Tested on Congress Street Expressway." Cook County Highways, Vol. 11, No. 4, Sept. 1963.

Information gathered in 18 months has identified bottlenecks and has led to experimentation with traffic control. As a first step, the project is testing the metering of vehicles entering the expressway by way of ramps. Red and green lights stop and start vehicles at the ramp entrance, spacing them at intervals suited to the volume of main lane traffic. The interval may be changed as traffic changes and the ramp may be closed for periods of time if the situation requires.

In addition to the light signals, advance signs with changeable panels advise motorists approaching the ramp on First Avenue of whether the ramp is open or closed at the moment. When the ramp is closed, it is presumed that motorists will either go to another ramp or will leave the expressway and use a parallel surface street.

The immediate objective of the surveillance project as stated by the director, Adolf D. May, Jr., is to "develop, to operate and to evaluate a pilot network information and control system to reduce travel time and to increase traffic flow."

6. "11 States Join Michigan in First Experiment of Electronic Traffic Control." Michigan Contractor and Builder, Vol. 57, No. 32, Nov. 1963.

Eleven states have joined Michigan in the operation of the nation's

first experiment in the electronic control of freeway traffic. Comprehensive studies of freeway traffic and driver behavior and their effects on traffic flow which have been undertaken will be completed and new studies will be started to evaluate lane, speed and ramp controls.

The study is being conducted on a 3.2-mile section of the Lodge Freeway in midtown Detroit. The Lodge Freeway is one of the world's busiest highways. It carries an average of 160,000 vehicles per day on week days and up to 7,200 vehicles per hour in one direction during rush hours.

The 3.2 miles of freeway under study are covered by 14 closed-circuit television cameras which have wide angle and telescopic lenses. They are operated by remote control from a control center where all data is collected. Traffic volume information is obtained by ultrasonic detecting equipment. Traffic is controlled by 21 overhead lane and speed control signals. Remotely controlled signs are on the entrance ramps of the freeway. They allow the control center to close ramps and prevent overloading of the freeway during rush hours.

7. May, A. D., "Experimentation with Manual and Automatic Ramp Control," Highway Research Record 59, Jan. 1964.

This paper describes the planning, conduct and evaluation of a series of experiments with freeway ramp control undertaken for the purpose of improving network operations.

The development of the control plan included the identification of the critical section, determination of the period of time and degree of control, estimation of the redistribution of traffic, and re-evaluation of system operations. A comprehensive set of measurements was obtained for the network, including expressway and major arterials, for three weeks with freeway ramp control. The ramp control consisted of partially closing one on-ramp and metering traffic at a second on-ramp. The effect on the network of the freeway ramp control was evaluated on the basis of vehicle-minutes and vehicle-miles of travel for each link, route, and for the total network. The results indicate that travel time on a network basis was reduced by freeway ramp control.

8. Gervais, E. F., "Optimization of Freeway Traffic by Ramp Control," Highway Research Record 59, Jan. 1964.

This paper describes a 1-week experiment into entrance ramp control conducted on the John C. Lodge Freeway in Detroit. Control

consisted of completely closing a ramp during certain periods. The control equipment and procedure is presented and an analysis of the effects of control given.

9. Drew, Donald R., "Theoretical Approaches to the Study and Control of Freeway Congestion." Texas Transportation Institute Research Report 24-1, Jan. 1964.

The problems of freeway operation and control are discussed and it is shown how they can be described by deterministic mathematical models. By showing a generalization and comparison of macroscopic and microscopic models of traffic flow the applicability of these deterministic models to freeway traffic is readily seen.

The need for a more sensitive indicator of congestion than density, led to the formulation of the moving queues model. The expected number of vehicles per moving queue provides a quantitative index of congestion. The congestion index developed offers more than a subjective means of evaluating freeway performance. An automatic control system, based on moving queues, would have many advantages.

10. Wattleworth, J.A., Berry, D.S. "Peak-Period Control Systems for Urban Freeways" Traffic Engineering, Vol. 34, No. 12, Sept. 1964.

Review of special control techniques to be used in peak-period freeway control system; possible ways in which each might be incorporated into final control system are discussed; freeway system is considered to include one-directional roadway of freeway and its ramp terminals which carries traffic in peak direction; system operates independently from freeway roadways carrying traffic in opposite direction; two general types of controls are considered.

11. Perchonk, K., and Hurst, P., "The Effect of Lane Closure Signals upon Driver Decision-Making and Traffic Flow," Division of Highway Studies Institute for Research, State College, Pennsylvania, March, 1965.

The comparative effectiveness of two types of alerting signals for lane closure was studied in terms of traffic flow characteristics and driver decision-making correlates (viz., responsiveness/confusion, risk taking predisposition, risk taking, and hazard). In addition to improvements in terms of several traffic flow characteristics, results showed the system affording the earlier warning to be superior in terms of decreased driver confusion and hazard in gap acceptance.

12. Drew, D. R., "Deterministic Aspects of Freeway Operations and Control." Texas Transportation Institute Research Report 24-4, June, 1965.

Existing theories of traffic flow may be classified as either stochastic or deterministic. The stochastic models are based on the classical subjects of queueing theory, mathematical probability and stochastic (variable) processes. The deterministic models of traffic flow are based on writing suitable desc iptions of the flow of vehicular traffic in the form of differential equations, and then solving these equations for observed boundary conditions. This report deals with the deterministic aspects of flow and operations.

Utilizing the analogy of a one-dimensional compressible fluid, a generalized macroscopic model of traffic flow is formulated and tested against the measured characteristics. The model is statistically significant and conceptually realistic when applied to freeway flow. A generalized microscopic model is also formulated, based on the car-following theories. Solution of the macroscopic and microscopic equations yields equivalent equations of state.

A comparison of the congestion predicting attributes of the two control parameters--optimum speed and optimum density--yielded close agreement in defining the time of incipient congestion throughout the length of the Gulf Freeway.

13. Drew, D. R., "Stochastic Considerations in Freeway Operations and Control." Texas Transportation Institute Research Report 24-5, June, 1965.

The primary characteristics of traffic movement are concerned with speed, density, and volume. Additional characteristics, associated with the traffic stream, are the transverse and longitudinal distribution of vehicles. The stochastic aspects of the freeway traffic phenomenon are based on describing the longitudinal distribution of traffic mathematically. The Erlang frequency distribution is utilized to describe the distribution of individual vehicles, and a "moving queues" model is formulated to explain the tendency of vehicles to platoon. Applications of the stochastic approach to traffic operations, freeway surveillance, and geometric evaluation and design are suggested.

14. Haynes, J. J., "Some Considerations of Vehicular Density on Urban Freeways." Texas Transportation Institute Research Report 24-6, April 1965.

This report includes parts of a general study of the various aspects

of vehicular density for use in the control of freeway traffic. Density is herein considered as a possible control parameter of a freeway operational system.

The principal features of existing methods used to measure or estimate density are reviewed. There are two basic methods involved. One is a process in which density is estimated on the basis of speeds and volumes which are sensed at a point. The other method, which is not yet operational, involves the actual measurement of the density, or concentration of vehicles in a space.

Results of aerial photographic studies of the Gulf Freeway in Houston are utilized to show how density may be related to volume as to certain geometric features of the freeway facility.

A field study method is described which yields continuous values of vehicular concentration on certain sections of a freeway. The analysis of the data demonstrates a means of establishing optimum, or critical, freeway concentration values and provides a means of identifying critical sections on a freeway which exhibit recurring high densities.

15. Wattleworth, J. A., "System Demand-Capacity Analysis on the Inbound Gulf Freeway." Texas Transportation Institute Research Report 24-8, October, 1964.

The prime objective of this study was the development and evaluation of a study technique which would permit the operational analysis of a one-directional freeway system turning its peak period. After the technique was developed it was used to analyze the peak period operation of the inbound Gulf Freeway with specific consideration given to the following objectives:

1. to identify the critical bottlenecks,
2. to determine the capacity flow rates at each of the bottlenecks,
3. to determine for five-minute time periods the demand rates at each entrance to the inbound freeway,
4. to determine for five-minute time periods the demand rate at each critical freeway bottleneck
5. to determine by how much and for how long the demand exceeds the capacity at each bottleneck,
6. to interpret these data in terms of the type of control system required to prevent congestion,
7. to obtain data suitable for the "before" portions of "before and after" studies to be used for evaluating control experiments, and
8. to use the data to predict the effect of control and/or geometric

design changes.

These data were also used to test the hypothesis that the development of congestion at a freeway bottleneck can decrease the flow rate.

16. Pinnell, C., Drew, D. R., McCasland, Wm. R., Wattleworth, J. A., "Inbound Gulf Freeway Ramp Control Study I." Texas Transportation Institute Research Report 24-10, December, 1964.

This report contains the background, development, and results of Ramp Control Study I conducted as part of the "Level of Service" project on the inbound Gulf Freeway. This first study was limited to the entrance ramps on the inbound Gulf Freeway from Wayside Drive to the downtown distribution system during the morning peak period. The control study was conducted on nine weekdays from August 4 to 14, 1964. The controls which were tested were fixed-time controls, i. e, they were not traffic adjusted. The development of the control plan utilized "historical" data which were collected from January to April, 1964. The approach or philosophy used in the development of this plan was to estimate the demand rate and capacity flow rate at each entrance ramp merging section from Wayside Drive to Scott Street and to control each entrance ramp in this section as severely as needed to keep the demand less than or equal to capacity.

17. Drew, D. R., "Gap Acceptance Characteristics for Ramp-Freeway Surveillance and Control," Texas Transportation Institute Research Report 24-12, July, 1965.

This investigation determined gap acceptance characteristics and merging delay characteristics for six inbound entrance ramps on the Gulf Freeway Surveillance and Control Project.

Merging vehicles were divided into two groups--those in which the driver rejected gaps before finally accepting a gap and those in which the driver of a ramp vehicle accepted the first gap. The former was referred to as "stopped" vehicles and the latter "moving vehicles." The critical gap for stopped vehicles was found to be about 20 percent higher than for moving vehicles. In addition, it was concluded that the critical gap (median) for the merging maneuver from an entrance ramp is independent of the freeway volume but is apparently affected by ramp geometrics and ramp controls.

A distribution of critical gaps was formed and fitted to a gamma distribution. Merging delay values calculated using this distribution were shown to be higher than those calculated assuming that all drivers

have the same fixed critical gap. The calculated values were also compared to observed merging delays.

If the distribution of time spent by merging vehicle at the head of the queue is approximated by a gamma distribution, the entrance ramp merging operation may be considered within the context of classical queueing theory. Based on this queueing model, a ramp metering technique was developed which takes into account the individuality of entrance ramps. Finally, it is shown how the need exists for an automatic ramp control technique combining the microscopic approach developed in this paper combined with the systems or macroscopic approach which has been used as the basis for the past manual ramp metering experiments on the Gulf Freeway.

18. Pinnell, C., Drew, D.R., McCasland, Wm. R., Wattleworth, J.A., "Inbound Gulf Freeway Ramp Control Study II," Texas Transportation Institute Research Report 24-13, July 1965.

This report presents the development of, preparations for, and results of the Inbound Gulf Freeway Ramp Control Study II, which was conducted between January 26 and March 12, 1965.

In this study four entrance ramps were closed and one entrance ramp was manually metered at predetermined rates. This study was highly successful but pointed to the need to control additional ramps between Wayside Drive and the Reveille Interchange to further improve freeway operations and to permit greater use of ramp metering and less use of complete ramp closure (by spreading the excess demand over more ramps). The present study was developed to fill this need and to allow the evaluation of a trial ramp control signal installation at the Dumble entrance ramp.

In addition, the traffic operation after termination of the control study was also studied and these results are presented. Evaluation of the operation during the control period centered mainly on the freeway but also included the inbound frontage roads and the arterial street system.

19. Wattleworth, J.A., "Peak-Period Analysis and Control of A Freeway System." Texas Transportation Institute Research Report 24-15, October 1965.

This paper presents some of the possible applications and advantages of another means of operating a peak-period ramp metering control system. The method involves the use of total flow which must

be maintained at levels less than or equal to the capacity at each freeway bottleneck. This control philosophy permits use of the continuity characteristics of traffic flow, thereby making system considerations possible. Previous techniques can necessarily be concerned only with the operation of individual merging areas and each can theoretically maintain a smooth merging operation at each entrance ramp. However, in many instances bottlenecks occur at locations between ramps, frequently caused by grades. Each ramp is one member of a system and the operation on one affects the operation of the system. It is desirable that the control system take this interdependency into account.

The discussion of the control system is presented in three parts. The first concerns the operation at individual ramps. The second is the consideration of the operation of the entire system and the third is operation during reduced-capacity situations, such as occurrences of accidents, disabled vehicles, etc.

20. Pinnell, C., Wattleworth, J. A., McCasland, W. R., and Drew, D. R., "Evaluation of Entrance Ramp Control on a Six-Mile Freeway Section," presented at the Highway Research Board Annual Meeting, Jan. 1966.

A pilot project was initiated by the Texas Transportation Institute in September 1963 with the basic aim of developing an automatic surveillance and control system for the Gulf Freeway in Houston, Texas. This work has progressed through basic studies of the operation on the Gulf Freeway to experimental control studies.

The first control study, conducted in August 1964, involved only a limited section of the Gulf Freeway but furnished the basic technology for a much more extensive control operation. This study, in effect between Jan. 26, 1965, and March 12, 1965, involved the closure or metering of eight inbound entrance ramps during the morning peak period.

This report furnishes the results of studies conducted before, during, and after the control plan was in effect. The development of the control procedure and the effect of the controls on freeway and surface street operation is presented and discussed. A discussion of the results of a study of public opinion regarding the control action and probable future research in the area is summarized.

21. Santerre, G. L., "An Investigation of the Feasibility of Improving Freeway Operation by Staggering Working Hours." Texas Transportation Institute Research Report 24-16, May, 1966.

This research investigates the feasibility of staggering working hours in Houston Texas and evaluates the impact that staggered working hours of selected traffic generators would have on the morning peak period operation of the Gulf Freeway in Houston.

22. Pinnell, C., "Progress Report on the Gulf Freeway Surveillance and Control Project," Texas Transportation Institute Research Report 24-17, July, 1966.

This report gives a concise and comprehensive picture of the surveillance and control project through the fiscal year 1965-66. The project scope and objectives are given along with a Projected Work Plan for the Level of Service Project. Some of the initial accomplishments discussed are the implementation of a freeway control plan, Control Study I and Control Study II.

23. Drew, D. R., McCasland, Wm. R., Pinnell, C. and Wattleworth, J. A., "The Development of an Automatic Freeway Merging Control System," Texas Transportation Institute Research Report 24-19, Jan. 1967.

A prototype merging controler was designed, constructed and installed at an entrance ramp on the Gulf Freeway in Houston. It has the capability of operating under one of four different modes of entrance ramp control. This report describes its operation and gives the results of preliminary evaluation studies.

24. Buhr, J. H., "Freeway Entrance Ramp Merging Control Systems," Doctoral Dissertation, Texas A&M University, College Station, Texas, Jan. 1967.

This dissertation deals with the control of freeway entrance ramps for the purpose of improving freeway operating conditions as well as aiding an entering driver in affecting the merging maneuver. A control function is first formulated according to which the control system should be operated and then evaluated through an investigation of its parent relationships. These parent relationships are, firstly, the gap acceptance characteristics of merging drivers and secondly, the gap stability characteristics displayed by freeway gaps as they traverse a section of highway immediately upstream of an entrance ramp. The control function applies for metering vehicles one at a time as

well as for metering of multi-vehicle platoon.

In a discussion of the applications of this research to the control of an entrance ramp, a hypothetical controller is suggested and a control chart developed from the control curves by which the settings on the controller can be determined.

E. TRAFFIC SURVEILLANCE

1. Janicki, E., "Television for Traffic Control," Public Works, Vol. 86 No. 12, Dec. 1955.

Trial use in Detroit of television cameras to help halt jams on several new expressways; under experimental program, TV screens pick up traffic on closed circuit cameras along route; as trouble is spotted, traffic control plan immediately to put into operation; calls go to engineers for operation of lane and ramp controls which prevent additional traffic from coming to expressway.

2. Malo, A. F., and Head, R. S., "The Role of Television in Traffic Control," Proceedings Highway Research Board, Vol. 35, 1956.

Average daily traffic on expressways is greater than was expected when they were built and traffic volumes are exceptionally high during peak hours. In such conditions an accident causes instantaneous congestion. With a view to minimizing this congestion, an experiment has been carried out by the Detroit Department of Streets and Traffic in conjunction with the Michigan Bell Telephone Company in the use of television for traffic control. The preliminary work and the difficulties encountered, necessary ancillary equipment and technical aspects of the problem are described and discussed. It is thought that the cost of control by means of television might be small compared with the economic advantages to be derived from its use.

3. Ricker, E. R., "Monitoring Traffic Speed and Volume," Traffic Quarterly, Vol. 13, No. 1, Jan. 1959.

A traffic monitor consisting of experimental radar sensing units has been installed on the New Jersey Turnpike, U.S.A. A brief description is given of the principle of the device and the method of installation. Tables and graphs are given to illustrate the information obtained. It is claimed that the monitor will enable capacity to be calculated accurately in terms of existing traffic flow, and that predictions will be possible of the frequency with which congestion will occur under existing road conditions.

4. Sands, L. G., "New Jersey Turnpike Utilizes Electronics for Traffic Surveillance," Public Works v 90, 3 March 1959.

Three radar sensing units, suspended over each of three southbound lanes of turnpike near Linden, N. J., count number of vehicles

and report their speed; information is transmitted over leased telephone circuits in form of audio tones to turnpike headquarters building which comprises traffic monitors registering data and computing averages.

5. Foote, R.S., Crowley, K.W., Gonseth, A.T., "Development of Traffic Surveillance Systems at Port of New York Authority," Traffic Engineering vol 32, no. 9 June 1962.

System to obtain vehicle speed information with respect to preventing shock waves, removing disabled vehicles, and determining best use of reversible roadways for Holland and Lincoln Tunnels in New York, N.Y.

6. Cottingham, K.E., "Proposed Surveillance System on Seattle Freeway." Traffic Engineering vol. 32, no. 9, June 1962.

Systems of operational surveillance of density type and closed circuit television type, integrated with control center and ramp intersection signal controllers; computer mastered traffic signal control system on city streets for handling "off-ramp" traffic of reversible roadways; problem of metering traffic entering freeway from other freeways where no signalized intersection exists.

7. Gervais, E.F., "John Lodge Freeway Surveillance Systems," Traffic Engineering vol. 32, no. 10, July 1962.

Experimental research on freeway traffic surveillance conducted to demonstrate how latest developments in electronics and other technological subjects can be applied to freeway operation.

8. Hagenauer, G.F., "Chicago Expressway Surveillance Research Project." Traffic Engineering, vol 32, no. 10, July 1962.

Project for observing highway operations by Chicago Area Traffic Subcommittee; installation of pilot research system for detecting operating characteristics of expressway at various points along its length to determine which characteristics could be most useful to display quality of operation.

9. Richard, C.L., and Bushnell, K., "Television Equipment for Traffic Surveillance," Highway Research Record, No. 10, 1963.

A project has been undertaken to evaluate the use of surveillance, traffic control and sensing equipment, and to investigate how such equipment can be used to study and improve traffic flow on freeways.

A closed-circuit television system which employs small vidicon tubes permits observation during the hours of darkness as well as in daylight. The camera and circuit are described and illustrated. The problems encountered on the John C. Lodge Freeway, where 14 television cameras are installed about 1/4 mile apart, are explained. From the control center it is possible to observe traffic, see accidents and direct aid to the sites, operate traffic control devices and assess the results obtained by vehicle-sensing equipment.

10. DeRose, F. Jr., "Lodge Freeway Traffic Surveillance and Control Project: Development and Evaluation", Highway Research Record, no. 21, Jan. 1963.

Analysis and evaluation of characteristics and accessories of closed circuit television system for viewing urban freeway traffic and aiding in traffic control; system consisted of cameras, monitors, transmission equipment, and accessories. Some typical research studies using television system are also described.

11. May, A. D., Athol, P., Parker, W. and Rudden, J. B., "Development and Evaluation of Congress Street Expressway Pilot Detection System", Highway Research Record 21, Jan. 1963.

12. Martin, H., "TV Aids Traffic Control." Traffic Engineering and Control, June 1963.

Use of TV for traffic observation and urban traffic control in Munich, West Germany. By means of TV camera, traffic can be monitored from Traffic Center, and programming of automatic installation centrally adjusted in light of information obtained. TV monitoring can be used for overriding central control of individual phases. Green and amber phases can be held to meet traffic conditions.

13. "Seattle Freeway Traffic Handled by TV Cameras." Western Construction, Vol. 38, No. 9, August 1963.

One operator, aided by 11 TV cameras, will control traffic on the Seattle Freeway now under construction. According to the local traffic engineers the system will represent the most advanced and effective remote control network, and at the same time be uncomplicated. The procedure and equipment will be the most advanced in the nation, although it will not be the first use of such implements for traffic control. The systems in use at Detroit and Chicago were added to existing highways, whereas the Seattle installation will be designed as part of the freeway program.

The Seattle Freeway, basically an 8-lane highway, will be supplemented with a 4-lane reversible roadway for a length of 7 1/2 miles. Normal traffic will move on four lanes in both directions, with the 4-lane reversible roadway brought into operation during morning and afternoon peak hours. The control system will automatically meter the traffic and operate all control devices along the reversible section. The operator will have control of 11 remote television cameras which will be located at strategic points along the freeway. This system will enable him to see conditions prior to operating the control system. These controls will activate barriers and swing gates to direct traffic and will also meter the necessary traffic signals to provide a continuous smooth flow of traffic.

14. Gervais, E. F., "National Proving Ground for Freeway Surveillance, Control and Electronic Traffic Aids," Proceedings of the Conference on Traffic Surveillance, Simulation and Control, Washington, D. C., Sept. 1964.

15. May, A. D., "Chicago Area Expressway Surveillance Project," Proceedings of the Conference on Traffic Surveillance and Control, Washington, D. C., Sept. 1964.

16. Cottingham, K. E., "Seattle Freeway Electronic Control and Closed Circuit Television," Proceedings of the Conference on Traffic Surveillance, Simulation and Control, Washington, D. C., Sept., 1964.

17. Pinnell, C., Drew, D. R., McCasland, W. R., and Wattleworth, J. A. "Gulf Freeway Surveillance Project," Proceedings of the Conference on Traffic Surveillance Simulation and Control, Washington, D. C., September 1964.

18. Foote, R. S., "Vehicle Tunnel Surveillance to Improve the Level of Traffic Service," Proceedings of the Conference on Traffic Surveillance, Simulation and Control, Washington, D. C., Sept. 1964.

19. "Traffic Surveillance Trial at Vauxhall Cross." Surveyor, vol. 74, No. 3784, Dec. 1964.

The Ministry of Transport is running a trial of Decca Radar Ltd. traffic surveillance equipment in the Vauxhall Cross area. The system, uses the Decca "Colormatic" traffic map which shows traffic movement over a large area at a glance. Vehicle detectors placed at 10 points on the road system operate colored lights on the map to show what vehicles are doing at each point: green arrows are illuminated

when traffic is moving at 10 mph or over, amber dots show when speed drops below 10 mph, and red arrows indicate that traffic has been stationary for more than half a minute.

The Vauxhall Cross scheme will be in operation 24 hr/day for the next 3 mo. for study by the MOT, police and local authorities. It may well prove to be an ideal traffic aid for small- and medium-sized towns with a serious traffic problem but not the finances to provide a full computer system.

20. Surti, V. H., "Effect of Television Surveillance on Police Response Time to an Urban Freeway Incident." Presented at the Annual Meeting of the Highway Research Board, Jan. 1965.

The John C. Lodge Freeway from the Edsel Ford Interchange north to the Davison Interchange has been under television surveillance since January 1961. This surveillance system was in part-time surveillance operation (6:00 a.m. to 8:00 p.m. on weekdays) with a control system of variable speed signs and lane control signals since May 1962. From the outset, manual logs were maintained recording information pertaining to incidents which affected either the traffic lanes or refuge shoulders. Prior to operation of the control system, police were notified only when an incident was a serious accident in which injury was evident or seemed likely. When the control system was put into operation, a policy of notifying the police of all incidents which affected traffic lanes within the visual range of the TV cameras was instituted. Since the manual logs were maintained and "before" and "after" notification periods existed, an attempt was made to determine whether notification had reduced response time to an incident by an official agency.

21. Pinnell, Charles, "Gulf Freeway Surveillance and Control Project," Traffic Quarterly, January, 1966.

F. COMPUTER CONTROL OF TRAFFIC

1. Overmyer, R.A., "Philadelphia's Electronic Controlled Signal System," Traffic Engineering and Control, Vol. 2, No. 5, 1960.

The paper describes the "PR" system and how it works in the downtown area of Philadelphia.

2. Casciato, Leonard, and Cass, Samuel, "Pilot Study of the Automatic Control of Traffic Signals by a General Purpose Computer," Electronics in Traffic Operations, Highway Research Board Bulletin 338, 1962.

The authors describe the initial, small signal system in Toronto. The modes of control are described in general terms as well as the mechanics of setting signals. An economic analysis of the pilot study is included.

3. Freer, J.A., "Los Angeles Installs America's First Computer System for Traffic Control", Traffic Engineering and Control, Vol. 4, No. 3, 1962.

The author briefly describes the Los Angeles digital system which performs the functions of the more familiar "PR" analog control system.

4. Irwin, N.A., "Optimizing Traffic Flow with Electronic Computer," AASHO Committee on Electronics pt 7, 1962.

Experimental project carried out in Toronto, Canada, metropolitan area to demonstrate that electronic computer could be connected into existing traffic signal network to provide flexible, reliable, and powerful coordinated signal system free of most of the limitations of existing traffic signal control equipment. Suggestions for wider application of computer control are made.

5. Miller, A.J., "A Computer Control System for Traffic Networks." Paper presented at the 2nd International Symposium on the Theory of Road Traffic Flow, London, June 1963. Univ. of Birmingham, Graduate School in Highway and Traffic Engineering, Pub. No. 3, 1963.

A data-sampled system is described for the computer control of traffic in urban networks. A digital computer is fed with data from detectors placed at the approaches and stop lines for every junction. Three forms of control are mentioned in this paper; namely, timing control, quantity control, and route control. Of these, only the first

is described in detail.

In the timing control system proposed, the computer scans each junction at regular intervals (about every 2 sec.) and makes a decision as to whether to change the signals or leave them as they are. These decisions are based on estimates of the relative delays which will be incurred if the signals are changed immediately or at subsequent intervals. The signals are left unaltered unless it appears that least delay will result from an immediate change.

To determine the effectiveness of the proposed timing control system, a program has been written to control computer-simulated traffic. Preliminary results suggest that the cost of delays saved by operating a computer control system such as that described, compared with the best existing alternatives, should exceed the additional installation and operating costs but possibly not by a great amount.

6. Grimsdale, R.L., Mathers, R.W. and Sumner, F.H. "An Investigation of Computer-Controlled Traffic Signals by Simulation." Proc. Institution of Civil Engineers, Vol. 28, June 1963.

Some experiments in computer-controlled traffic signals have been done using the Mercury digital computer at Manchester University. The road network which contained the traffic signals was simulated on the same computer. The object of the experiments was to investigate some methods of centralized computer-control of traffic signals and in particular the provision of signals indicating the best routes between points in the network. The idea behind the control methods, designed to eliminate traffic jams, was to limit entry of vehicles to insure freedom of movement for vehicles in the heart of the network. The operation of the method of routing control proved successful in the model, although the improvement in flow rates was not great.

7. Traffic Control by Computer Increases Street Capacity." Public Works Vo. 94, No. 8 Aug. 1963.

A centralized traffic control scheme presently being installed in Toronto, Ontario is described. The traffic signal system has unlimited flexibility in the manner in which signals adjust to traffic requirements and built-in facilities for studying methods of control and making long range traffic plans. A pilot study to test new system under actual traffic conditions indicated decrease of 11% in average delay per vehicle during evening rush hours and of 25% in morning rush hours while congestion was reduced by 28%. Computer statistics are given and the system operation explained.

8. Irwin, Neal A., "The Toronto Computer-Controlled Traffic Signal System," Proceedings of the Interdisciplinary Clinic on Instrumentation Requirements for Traffic Control Systems, New York, Dec. 1963.

This paper is a study of the full Toronto system using a Univac 1107 central computer. Developments in control techniques beyond the Pilot Study are described. Particularly concerned with hardware characteristics of the system.

9. "Highway Traffic Control by Data Processor." Surveyor Vol. 123, No. 3746, Mar. 1964.

A new system of complete road traffic control by linking of traffic signals and detectors to data processor will reduce accident rate, increase traffic flow, and defer costly urban redevelopment. Working on the principle of fixed time cycles, but depending upon number of vehicles presenting themselves at intersections, green time can be borrowed or lent, while overall time cycle is maintained as constant. 'Rotrac' system enables existing and proposed roads to be used to limit of their capacity.

10. Downey, H. E., "Computer Control of Main Artery Traffic Flow," Data Systems Engineering, Vol. 19, No. 3, Mar. 1964.

A system developed by General Railway Signal Co. for controlling traffic on Buffalo, NY Main Street is described. The system is based on the concept of "lane occupancy," for determination of which ultrasonic sampling techniques and telemetry are used. Data from detection system are fed into computers that select offset and cycle length of traffic signals.

11. Casciato, Leonard and Cass, Samuel, "Progress and Experience in Toronto Traffic Control System," Proceedings Conference on Traffic Surveillance, Simulation and Control, September 1964.

The authors describe the 500 signal control system in Toronto using a Univac 1107 central computer. They also describe the manner of utilization of the computer, signal modifications, and data accumulating capabilities of the system.

12. Rudden, J. B., "Central Control of Traffic Signals," Traffic Engineering, Vol. 37, No. 4, January 1967.

This paper is a very general treatment of the philosophy of central

control. A functional analysis of operation of detectors, central computer and signal devices in such a system without reference to a specific configuration.

G. QUALITY OF FLOW - LEVEL OF SERVICE

1. Rothrock, C.A., "Urban Congestion Index Principles." Highway Research Board, Bulletin, No. 86, 1954.

The author discusses the need for a method of measurement and evaluation of traffic congestion. He outlines the concepts of operational characteristics, freedom of movement and volume-to-capacity ratio as possible approaches to the development of a "Congestion Index."

2. Greenshields, B.D., "Quality of Traffic Transmission," Proceedings of the Highway Research Board, Vol. 34, 1955.

The author suggests some quantitative measures of traffic congestion by the development of a "Quality of Flow Index" based on the average speed and the magnitude and frequency of speed changes. He also suggests an "Efficiency Index" as a measure of both the quantity and quality of traffic flow.

3. Rothrock, C.A. and Keefer, L.E., "Measurement of Urban Traffic Congestion," Highway Research Board Bulletin, 156, 1957.

The authors utilize the parameter of travel time in an attempt to evaluate the level of service on a city street.

4. Provins, K.A., "Environmental Conditions and Driving Efficiency." Ergonomics, Vol. 2, No. 1, 1958.

The paper is a review of work in the field of environmental effects on human performance with special reference to problems of driving efficiency. It is concerned principally with the effects of low and high environmental temperatures, and of air pollution by carbon monoxide, on sensor-motor performance at tasks related to driving. There are many papers and reviews dealing with the general problem of environmental and occupational efficiency but relatively few concerned directly with motor vehicle driving. This is probably due to difficulties and dangers of experiments on the roads which might lead to reduction of driving efficiency and to the intrisic difficulty of measuring driver performance. This review must be regarded therefore as a guide to the possible effects which environmental conditions may have on motor vehicle driver performance and a pointer to the need for further research more pertinent to the driving problem itself.

5. Hall, E. M., and George, S., Jr. "Travel Time - An Effective Measure of Congestion and Level of Service." Highway Research Board Proceedings, Vol. 38, 1959.

The effectiveness of travel time as a measure of congestion and quality of urban traffic service is discussed. The importance of travel time, not only for day-to-day operations but also for long-range planning of streets and highways, is stressed. In discussion field studies in the San Diego area, the authors stress the simplicity of data collection and analysis, and the various effective presentations evaluating the quality of urban street service. The presentations have proven to be easily understood by the average layman, and useful to technicians and in management. The cost of conducting the travel time studies is summarized.

6. Michaels, R. M., "Tension Responses of Driver Generated on Urban Streets," Highway Research Board Bulletin 271, 1960.

7. Brenner, Robert, "A Quantitative Evaluation of Traffic in a Complex Freeway Network." Highway Research Board, Bulletin 291, Jan. 1961.

The proposition that travel time is a fundamental dependent variable in the analysis of transportation systems is developed along with several corollary concepts. The proposition and some of the derived concepts were put to test in a detailed investigation of traffic in a part of the freeway network in downtown Los Angeles.

License plate methods were used to obtain both travel time and the relative percentages of traffic flow in all the combinations of input-output freeways as well as freeway-ramp combinations. Speeds and headways were measured by lane at the output boundary of the network of interest which is on a freeway proper. Other covariates were classified volume counts by lane on the output boundary. A novel mailing questionnaire was used to establish the surface street paths that drivers pursue to get to the on-ramps of the network.

Representative of the hypotheses tested were: the effect of on- and off-ramp traffic on network travel time; the effect of multiaxle vehicles on network travel time; deduced effects that opening planned additional links of the freeway system will have on the existing network; deduced effects that closing a ramp would have on the network as well as on the adjacent surface streets.

Besides providing a quantitative description of traffic in the

selected network, the study demonstrates that mathematical models based on travel time can be applied to real situations. Although there can be no formal proof of the importance of these models, the fact that they yield useful information in this case suggests that more general applications might be considered.

8. George, H. P., "Measurement and Evaluation of Traffic Congestion," Bureau of Highway Traffic Yale University, 1961.

The author assumes that traffic inefficiency consists of two major factors: (1) time of operation or time loss and (2) driver inconvenience and discomfort. Traffic is then given a rating of congestion, R, according to the relation $R = D + f\left(\frac{D}{avb}\right)$ where D is the number of vehicles per mile, v is a coefficient of variation of the distribution of speeds, and a and b are constants. D is related to operating time and the second term introduces the discomfort element. Field work undertaken and analysis of data are explained and it is noted that values determined for total daily inefficiency may be used as indices for comparison purposes.

9. Guerin, N.S., "Travel Time Relationships." Bureau of Highway Traffic, Yale University, 1961.

Travel time is considered as one of the basic variables in the characteristics of a traffic stream, with particular emphasis on its relation to traffic density. Boundary curves are proposed and considered better than average curves for expressing this relation, which is not linear because the values of the regression coefficients depend on the range of traffic conditions observed and the duration of the observations.

10. Palmer, M. R., "The Development of Traffic Congestion." Bureau of Highway Traffic, Yale University, 1961.

This study deals with the behavior of drivers in a traffic stream as flow approaches the absolute capacity of a highway. The analysis was particularly concerned with the kinematic flow theory of Lighthill and Whitham and is a detailed study of the pattern of traffic at a bridge site on the Merritt Parkway during a 30-min period. The observed traffic behavior was in fairly close agreement with that indicated for a bottleneck by the theory. Queues of vehicles spaced closer than four seconds apart tend to slow down at a bottleneck, the reduction in speed being greater for long than for short queues. A relatively small increase in traffic load on a heavily loaded road can have a very big effect and may quickly triple average travel time over a considerable

distance.

11. Underwood, R. T., "Speed Volume and Density Relationships." Bureau of Highway Traffic, Yale University, 1961.

Analysis of results obtained at two sites indicates that there seems to be an exponential relation between space mean speed and traffic density on ordinary roads but it does not apply to motor roads. A generalized speed-flow diagram is given which consists of three zones (normal flow, unstable flow and forced flow), each specified in terms of probabilities.

12. May, A. D., and Wagner, F. A., "A Summary of Quality and Fundamental Characteristics of Traffic Flow." Michigan State University, Highway Traffic Safety Center, East Lansing, Michigan, 1961.

Two reports, entitled "A Study of Quality of Traffic Flow," and "A Study of Fundamental Characteristics of Traffic Flow," both published in 1960, are summarized. They describe work carried out in 1957 and 1958. The study on quality of traffic flow investigated the effects of various road features and frictions (medial, marginal and intersectional friction) on traffic operating characteristics such as speed, economy and safety of movement. Information on speed, changes of speed, stops, brake applications and fuel consumption in relation to time and distance of travel were obtained from a moving vehicle traveling along 41 selected road sections on urban expressways and other roads in Detroit, Lansing and East Lansing. Traffic volume recorders were placed near both ends of each section. A method for appraising the quality of traffic flow is developed. Research was included on the reliability of the moving car method, the applicability of statistical analysis to travel-time studies and the effectiveness of equipment used for traffic observations and measurements. To study the fundamental characteristics of traffic flow, information on traffic volume, lane usage, speed, density, and vehicle headways in terms of time and distance was collected at seven of the sites and analyzed. The interrelationships between these characteristics were also analyzed.

13. Harr, Milton E., and Leonards, Gerald A., "A Theory of Traffic Flow for Evaluation of Geometric Aspects of Highways," Highway Research Board Bulletin 308, 1962.

The authors take a somewhat more mathematical approach to the measurement of the quality of traffic flow as affected by a certain geometric feature. They propose an "F-factor" as a numerical rating of a particular geometric aspect, derived from an analogy with the one

dimensional flow of a compressible fluid.

14. Halen, C.E., Hall, E.M., and Johnson, A.A., "Travel Time-A Measure of Service and a Criterion for Improvement Priorities," Presented at the Annual Meeting of the Highway Research Board, Jan. 1963.

15. Platt, F.N., "A Proposed Index for the Level of Traffic Service." Traffic Engineering Vol. 34, No. 2, Nov. 1963.

An index called the "Level of Traffic Service Index" is proposed in this paper based on a systems framework of traffic observations. It refines Greenshields' "Quality of Flow Index" with additional factors related to driver satisfaction, effort and annoyance. Special attention is given to the different types of drivers and their objectives. Data for calculating the index of a particular highway can be obtained by a special vehicle-mounted instrument. The need for a Level of Traffic Service Index has been voiced by both engineers in traffic operations and economists involved in highway user benefit studies. Extensive research is recommended to substantiate and refine the proposed index so that it may some day become an acceptable international standard.

16. Schwar, J.F., and Taylor D.M.C., "The Speed Response Surface: Another Measure of Traffic Service," Unpublished, Dept. of Civil Engineering, The Ohio State University, 1965.

17. Drew, D.R., Keese, C.J., "Freeway Level of Service as Influenced by Volume and Capacity Characteristics." Highway Research Record No. 99, 1965.

This report deals with two main topics which affect traffic operation, and thus the level of service, on freeways. They are volume characteristics and capacity characteristics. The two main topics under volume characteristics which are considered are (1) peak rates of flow, and (2) lane distribution of vehicles on freeways.

The second section deals with freeway capacity characteristics including a theoretical approach to providing a rational relationship between capacity and level of service. An energy-momentum analogy is proposed as a quantitative approach to this relationship. In the third section, applications are made of these demand and capacity characteristics to freeway design and operation.

18. Drew, D. R., Dudek, L., "Investigation of an Internal Energy Model for Evaluating Freeway Level of Service." Texas Transportation Institute Research Report 24-11, June, 1965.

The objectives of this research fall into three phases: (1) theory formulation, (2) measurement of appropriate traffic characteristics for theory verification, and (3) recommendations for application. They include:

1. The formulation of an "energy" model of traffic flow which includes both "kinetic energy" and "internal energy."
2. Measurement of the acceleration noise on the Gulf Freeway to test the hypothesis that acceleration noise represents the "internal energy" of a traffic stream.
3. Determination of the effects of such geometrics as grades of the facility on acceleration noise.
4. Determination of the effects of operational control procedures such as ramp metering on acceleration noise.
5. Recommendations for application of energy parameters in freeway design and operations.
6. The application of the energy concept to the quantitative description of freeway level of service.

19. Surti, V. H. and Gervais, E. F., "Peak Period Comfort and Service Evaluation of an Urban Freeway and an Alternate Surface Street." The National Proving Ground for Freeway Surveillance, Control and Electronic Traffic Aids, Detroit, Michigan, August 1965.

20. Schwar, J. F., "Quality of Traffic Service," Traffic Quarterly, Jan. 1966.

21. Drew, D. R., Dudek, C. L., and Keese, C. J., "Freeway Level of Service as Described by an Energy-Acceleration Model," Presented at the Annual Meeting of the Highway Research Board, Jan. 1966.

22. Reddy, M. S., "Quantitative Evaluation of the Effect of Merging Vehicles on Freeway Operation," Dissertation, Texas A&M University, Jan. 1966.

H. TRAFFIC SIMULATION

1. Kell, James H., "Intersection Delay Obtained by Simulating Traffic on a Computer." Highway Research Board Bulletin No. 15, Dec. 1948.

This paper presents the results of the first phase of an extensive project involving the simulation of vehicular traffic at intersections. The model used in this phase consisted of the time simulation of an orthogonal intersection of two two-lane, two-way streets with the minor street being controlled by stop signs. Approximately 14,000 hr of traffic were simulated on an IBM 701 computer. Total intersection delay was the final output of the simulation. This is related to input volumes by multiple regression techniques. These results are compared to the output from the second phase (a signalized intersection) to provide factual data concerning the effect of installing a traffic signal at an intersection.

2. Glickstein, A., Findley, L. D., and Levy, S. L., "Application of Computer Simulation Techniques to Interchange Design Problems," Highway Research Board Bulletin, No. 29, Nov. 1950.

3. Trautman, D. L., Davis, H., Heilfron, J., Ho, E. C., Mathewson, J. H., Rosenbloom, A., "Analysis and simulation of vehicular Traffic Flow." California Univ. Institute of Transportation and Traffic Eng--Research Report No. 20, Dec. 1954.

Phenomena of traffic flow with significant questions pertinent to congested flow; vehicle delay at intersections related to traffic control; statistical behavior of congested merging traffic phenomena; programming method applicable to many large scale, high speed, general purpose digital computers. Bibliography.

4. Gerlough, D. L., "Simulation of Freeway Traffic by an Electronic Computer." Highway Research Board Proceedings, Vol. 35, 1956.

The electronic computer offers promise of becoming a powerful tool in studying the flow of traffic on freeways. To program such a problem for the computer the engineer must quantize time and distance. For input data he must have as a minimum a distribution of desired speeds and a distribution of input time-spacings. Additional phenomena which may be handled include vehicle length, following practices, passing practices, and time within system. For the treatment of such problems there are available two markedly different approaches each of which is discussed.

Exploratory studies indicate qualitative agreement between results and expected behavior.

5. Goode, Harry, H., Pollmar, Carl H. and Wright, Jesse B. "The Use of a Digital Computer to Model a Signalized Intersection." Highway Research Board Proceedings Vol. 35, 1956.

A method for modeling a signalized intersection on a digital computer is developed and used to estimate delays as a function of cycle time, turn fraction, green time and cars per hour. The method is compared with other techniques and a prognosis is made for its future use.

6. Goode, H. H., "The Application of a High Speed Computer to the Definition and Solution of the Vehicular Traffic Problem." Operations Research, Vol. 5, No. 6, Dec. 1957.

After an examination of the methodology used by the operations researcher, it becomes clear that the mathematical model is central to this methodology. It therefore becomes of interest to examine mathematical models. These are classified into analytic and numerical, as well as into deterministic or stochastic. Attention is then centered on the numerical stochastic model. The use of a computer in this connection is explored and the resulting model is discussed from the standpoint of operations-research methodology--all in connection with the vehicular traffic problem. Conclusions are drawn concerning the estimated usefulness of such a model in the future.

7. Helly, W., "Simulation of Bottlenecks in Single-Lane Traffic Flow," Proceedings, Symposium on the Theory of Traffic Flow, General Motors Research Laboratories, Warren, Michigan, Dec. 1959.

Bottleneck behavior of automobile traffic is simulated for environments where passing cannot occur and where vehicles neither enter nor leave the traffic stream. A microscopic "car-following" model simulates bottlenecks in traffic tunnels. The first bottleneck behavior assumes the headway of the n^{th} platoon vehicle is independent of n (the positions in the platoon). In second kind, the time headway increases with n. A theoretical behavior model for the bottlenecks of the second kind is developed as a Markov chain.

8. Gerlough, D. L., "Traffic Inputs for Simulation on a Digital Computer," Proceedings Highway Research Board, 1959.

The relative merits of observed inputs and generated inputs are

discussed. A method of generating Poisson inputs is described. Methods of adjusting the exponential to gain greater realism in time spacing of vehicles are discussed.

9. Perchonok, P. A., "Application of Digital Simulation Techniques to Freeway On-Ramp Traffic Operations." Highway Research Board Proceedings, Vol. 39, 1960.

This paper reports on a simulation study by digital computer of freeway on-ramp operations. With the techniques described, it is possible to determine some of the effects of changes in traffic volume, velocity, geometric design, etc. The basis for the simulation is the statistical analysis of data from a number of interchange locations which describes traffic flow and driver behavior in the merging process.

10. Wohl, M., "Simulation-Its Application to Traffic Engineering," Traffic Engineering Vol. 30, No 11, Aug., 1960, Vol. 31, No. 1, Sept. 1960.

Simulation has experienced wide-spread application in various fields of science and engineering. Until recent years, however, traffic engineering applications were limited to simulation which utilized physical models. With the rapid development of electronic digital computers it has now become feasible to consider simulation of vehicular traffic flow by mathematical or symbolic models. This type of simulation has tremendous potential for solving the everyday analysis and design problems facing highway and traffic engineers.

The first part of this paper seeks to define simulation, the major steps in the simulation process, and its applications to the field of traffic engineering. The second part illustrates the simulation process by following through a simulation program which deals with a specific, though simplified, design problem.

11. Miller, C. L., Lang, A. S., and Robbins, D. H. "650 Program Manual: Vehicle Simulation and Operating Cost System". Data Engineering Division, Dept. of Civil Engineering, Massachusetts Institute of Technology, Pub. 142, May 1961.

A set of digital computer programs has been developed to aid the highway engineer in the economic evaluation of alternative highway alignments. Specifically, these programs are intended to supplement the method outlined in the AASHO Road User Benefit Analyses for Highway Improvements Report for computing vehicle operating costs. The

report relies on graphical means to obtain operating costs for a given set of alignment and speed conditions. This information is both difficult and costly to keep up-to-date. The results of the computer programs, on the other hand, are as up to date as the input data used by the engineer.

This report is a manual which provides the highway engineer with sufficient information to run the programs on a basic IBM Type 650 Computer and tabulate the output on a 407 Accounting Maching. It does not attempt to cover the refinements of the logic and mathematics of the model. This aspect of the research is covered in the "Research Report on the Vehicle Simulation and Operating Cost System," Publication 143, Data Engineering Division, Department of Civil and Sanitary Engineering, Massachusetts Institute of Technology.

12. Stark, M. C., "Computer Simulation of Traffic on Nine Blocks of a City Street," Highway Research Board Bulletin 356, Jan. 1962.

A computer model has been constructed which simulates the volume and movement of traffic on a nine-block section of a city street. The simulated cars are reviewed every quarter-second and are moved according to rules for movement which have been built into the computer program. The simulation run on the computer produces two outputs. The quarter-second car positions are plotted on an oscilloscope and photographed. The result is a moving picture which can be shown in real time. The effect is comparable to viewing the traffic flow from a helicopter. The other output is a series of tables that catalogs all vehicles as they enter the model, clock and count them as they pass a key intermediate point, and, finally, check them out at the end of the course, counting them again and noting their individual running times. Other information is also furnished, such as type of vehicle, speed, and lane use. The tables thus furnish an abundance of quantitative data for measuring and evaluating the performance of the model.

13. Kell, J. H., "Analyzing Vehicular Delay at Intersections Through Simulation." Highway Research Board Bull. 356, Jan. 1962.

The first section of this paper describes the development of a simulation model for the intersection of two 2-lane two-directional streets, with one street being controlled by stop signs. The lack of adequate mathematical distributions describing traffic behavior and the field studies performed to obtain these distributions are discussed. The elaborate techniques used to test the logic of the model before beginning the analysis are also reviewed.

The second portion of the paper presents the simulation results. The variability of vehicular delay under constant traffic conditions is described and the relationships between vehicular delay and individual approach volumes and turning movements are formulated.

A brief discussion of the value of this research and the general applicability of simulation techniques to solving traffic problems is also presented.

14. Walton, J.R., and Douglas, R.A., "A LaGrangian Approach to Traffic Simulation on Digital Computers" Highway Research Board Bull. 356, 1962.

The technique described is designed to reduce computational effort by performing computations only for those times when vehicle interactions occur and for the vehicles affected. Traffic is simulated as it would appear to an observer in each vehicle. In the case of an extremely complex traffic situation with a large number of interactions, the computation required approaches by Eulerian techniques.

15. "Study of Electronic Devices as Traffic Aids: Annual Report." Transportation Engineering Center, Report No. 202-1. Engineering Experiment Station, Ohio State University, July 1962.

A coordinated program of research on the use of electronic devices as traffic aids has been pursued by The Ohio State University's Engineering Experiment Station, since 1959. Two earlier reports have been issued. The following accomplishments of the past eight-month period are provided in the following:

1. Progress in traffic dynamics with a view to the design of logic system can be summarized as follows:

(a) The IBM 1620 computer was programmed to simulate car-following and platoon dynamics through the use of the Hermann Equation which states that acceleration is proportional to the ratio of relative velocity and headway - $A = C (RV/H)$. The behavior of the first car is specified and motion of the following cars depends on time lags and bounded acceleration rates. Simulation continues until a collision or a stable platoon situation is reached.

(b) The Block Systems Dynamics have been analyzed for a servo-mechanism approach. Such a system activates blocks in a highway after the vehicle passes these blocks. Use of servo-mechanisms with the block system considered was found to be unsatisfactory over the range of velocity and traffic conditions normally encountered in highway traffic.

(c) The logic circuits and electronic circuitry of a rear zone of

influence control system have been developed.

(d) The mathematical model of the passing maneuver for the two-lane highway is written in terms of computer operations. It encompasses the velocities, platooning, and acceleration.

(e) A system for measuring and recording highway data has been developed. This system is based on a fine wire stretched across the highway.

2. The driving task has been examined with a view to the design of electronic systems. The following results involving the driving task were obtained:

(a) The early model of the driver-vehicle system placed the role of the driver as that of an error signal amplifier in a linear continuous feedback control system. Further research has shown that the driver reacts to both velocity and acceleration and is better explained as an integrator as well as an amplifier on the error signal.

(b) Driving simulator studies for the single-lane car-following situation show that the driver makes changes on the basis of decision points. These decision points may be a subconscious phenomenon.

(c) Driver variability studies were conducted on the stopping of a vehicle. Fatigue, driving experience, and the type of stop were investigated. Although interesting relationships were found with experience and type of stop, the general hypothesis that drivers will attempt to minimize the rate of change of deceleration and will not exceed a maximum deceleration was supported.

3. A study of the application of electronic control devices has been initiated and has investigated possible use in various highway situations, and under various degrees of application. The need for specific criteria for the use of electronics is pointed out.

16. Lewis, Russell M., Michael, H. L., "The Simulation of Traffic Flow to Obtain Volume Warrants for Intersection Control," Presented at the Annual Meeting of the Highway Research Board, Jan. 1963.

Several methods of traffic control have been developed for intersections. These include the basic right-of-way rule, stop signs, and various types of traffic signals. General warrants have been proposed for these methods of control based on vehicular volume, pedestrian traffic, accident records, and other factors. These warrants were developed in part from empirical data, but in some cases are little more than "rules of thumb." While significant effort has been devoted to the determination of warrants for fixed-time traffic signals, specific warrants for actuated signals are lacking.

One of the foremost problems in the development of warrants is the difficulty of determining the specific behavior of a general class of intersections. Computer simulation, however, offers tremendous possibilities in this area. Digital simulation possesses some unique properties when compared with more conventional methods. It has the important advantage of bringing the traffic facility into the laboratory for study under practically limitless conditions. Precise control of the dynamic traffic process can be maintained and many unwanted variables eliminated.

17. Kell, J. H., "Intersection Delay Obtained by Simulating Traffic on a Computer," Traffic Flow Theory, Highway Research Record 15, January 1963.

The paper reports on a digital simulation model and how it was used to develop volume warrants at a four-legged, right-angled intersection of a high volume major arterial sheet with a lower level minor arterial street. The major street had four travel lanes, the minor street had two travel lanes plus parking. Both were two way streets. Delays were measured and used as criteria for establishment of warrants.

18. Wohl, M., and Brand, D., "Applications of Simulation to Highway Traffic Design," Department of Civil Engineering, Massachusetts Institute of Technology, March 1963.

19. Saal, C. C., "Simulation of Highway Traffic by Computer," Georgia Institute Technology-School of Civ. Eng.-Georgia Highway Conference, 12th-Proc. 1963.

20. Ruiter, E. R., "The Effects of Random Traffic on the Accuracy of the Vehicle Simulation and Operating Cost System." Massachusetts Institute of Technology, Dept. of Civil Engineering, Research Rept. R63-3, July 1963.

This report describes a preliminary investigation of the effects of traffic interference and congestion on the accuracy of the "Vehicle Simulation and Operating Cost System." Presently, it is assumed that the vehicle population traveling over a given highway can be represented by a sample with each vehicle in this sample having only one limiting speed profile. No allowance is made therefore for variations in average speeds from one vehicle to another within a given class. This investigation attempts to determine the criticalness of variations in average speeds within a vehicle class and how these variations affect operating costs.

The Vehicle Simulation and Operating Cost System serves as an aid in the determination of highway user costs by calculating the costs of fuel and of travel time for a given section of alignment. This is accomplished by modeling or simulating the operation of a vehicle and determining the associated costs involved in the movement. Vehicle operating costs are a direct function of vehicle road speeds, engine RPM, vehicle tractive effort, and percent of full engine load. These four items are in turn directly related to certain highway design characteristics selected by the engineer. These characteristics include the vertical alignment of profile, the unbalanced side force caused by curves, the pavement type, and the operational restrictions placed on speed. The programs within the System take the above design characteristics on engine performance into account. These consequences are then converted into associated costs.

The effects of distributions of speeds are analyzed in detail by comparing the average operating cost of the average speed for a number of speed distributions. The results indicate that these two quantities are very nearly equal for all distributions studied.

21. Kell, J. H., "Results of Computer Simulation Studies as Related to Traffic Signal Control," Proceedings, Institute of Traffic Engineers, Aug. 1963.

The author reports on the results of 60,000 hours of simulated real-time for a single intersection with various flow rates and signal control configurations. A description of the model and the validation studies is included.

22. Katz, Jesse H., "Simulation of a Traffic Network," Communications of the ACM, Vol. 6, No. 8, Aug. 1963.

A brief but concise description of the TRANS simulation program developed by Thompson, Ramo Wooldridge to simulate traffic flow in an 80 signal network in the Rock Creek Park area of Washington, D. C.

23. Gerlough, D. L., "Simulation as a Tool in Traffic Control System Evaluation," Proceedings of the Interdisciplinary Clinic on Instrumentation Requirements for Traffic Control Systems, New York, Dec. 1963.

The paper describes the simulation of an 80 signal network in Washington, D. C. The formulation, operation and testing of the model is discussed. The manner in which the simulation has been used to evaluate and improve the signal control system in the area is also

described.

24. Constantine, T., "Simulation by Electronic Digital Computer," Traffic Engineering and Control, Vol. 5, 1964.

25. Gerlough, D. L., "Simulation of Traffic Flow," An Introduction to Traffic Flow Theory, Highway Research Board Special Report 79, 1964.

This general discussion traces the development of simulation in traffic engineering. A brief description of Monte Carlo techniques is presented, followed by examples of their application to several theoretical distributions. Descriptions are included of several models which have been developed for intersections, freeways, signal networks and tunnels.

26. Blum, A. M., "A General Purpose Digital Simulator and Examples of Its Application. Pt. III: Digital Simulation of Urban Traffic" IBM Systems Journal, Vol. 3, No. 1, 1964.

GPSS II, a general purpose digital system simulator, is described and some examples illustrating its application are given. Use of the simulator is discussed for problems associated with urban traffic studies. Included are simulation methods for intersections and networks, vehicular characteristics and input, and the network traffic mechanism. The general purpose simulator is employed to write a general traffic program used with data cards specifying the geometry, signal settings, statistical distributions, and other details of the particular network selected for simulation.

27. Baker, R. F., "Developments in Traffic Simulation and Control," Public Works, Vol. 95, No. 3, March 1964.

Well-balanced traffic research programs should cover traffic surveillance, traffic simulation, and traffic control; traffic surveillance enables observation of traffic, and recording of data on traffic operations; traffic simulation allows traffic problems to be considered in the laboratory; traffic control systems using electronic digital or analog computers can use results of traffic simulation and surveillance study techniques in developing control programs, thus providing optimum operation of street network.

28. Dawson, R. F., "Analysis of On-Ramp Capacities by Monte Carlo Simulation and Queuing Theory," Joint Highway Research Project, Purdue University, September, 1964.

The research report is concerned with the analysis of the capacities of three different freeway on-ramp designs--namely, on-ramps with no acceleration lane and stop-sign control, on-ramps with no acceleration lane and yield-sign control, and on-ramps with an acceleration lane and no sign control. The study included the development of criteria of defining both possible and practical capacities, the development of a deterministic queuing model for predicting possible capacity, the development of a Monte Carlo simulation model for the study of ramp flow under varying traffic conditions, the evaluation of vehicle delays and queue lengths incurred by on-ramp vehicles for various combinations of ramp and shoulder-lane traffic volumes, and the evaluation of possible and practical on-ramp capacities for the three different ramp designs.

Initial research efforts were concerned with the development of descriptors of the ramp situation. The distribution of headways between ramp vehicles was described by a hyper-exponential model. All ramp vehicles were assumed to enter the ramp system at a constant speed, controlled by the critical geometry of the area rather than by traffic. Ramp vehicle behavior in the system was defined by four factors--the spacing relationship with the preceding vehicle, acceleration-deceleration capabilities, the availability of gaps in the shoulder lane, and distributions describing gap-acceptance phenomena.

Shoulder-lane headways were described by a shifted-exponential model. Each shoulder-lane vehicle was assigned a speed upon entry into the system that was dependent only upon the volume of traffic in the shoulder lane. It was further assumed that the shoulder-lane vehicles proceeded through the ramp area at the speeds and headway spacing assigned at generation, without any interference from ramp traffic.

The various traffic descriptors were expressed in the mathematical mode and assembled for analysis into two different types of models--a deterministic queuing model for the analysis of possible ramp capacity, and a Monte Carlo simulation model for the analysis of practical capacity.

Because both models were constructed in the mathematical mode they were readily programmed for computer solution. The programs were coded in the FORTRAN IV and MAP languages for the IBM 7090/7094 System and were run on an IBM 7090.

The results obtained from the queuing-model analysis were reported in graphical form. The possible capacities of each of the three ramp designs were plotted as functions of shoulder-lane volume. Delay and queuing characteristics for a wide range of ramp and shoulder-lane volume combinations were obtained from the simulator. Practical capacities were defined for each of the three map designs by analyzing the delay characteristics relative to the criteria established for practical capacity in the definition of the same. Queue storage requirements on the ramp were found by an analysis of queuing characteristics at practical-capacity volume levels.

29. Stark, M. C., "Simulation of the Arterial Street," Proceedings of the Conference on Traffic Surveillance, Simulation and Control, September 1964.

Describes the development of a computer simulation of a nine block segment of 13th Street, N. W. in Washington, D. C. The model uses a cathode ray tube as an output device with vehicles represented by moving dots on the screen. Movies of the screen face illustrate the traffic movement in the system.

30. Kell, J. H., "Simulation of the Intersection," Proceedings of the Conference on Traffic Surveillance, Simulation and Control, Sept. 1964.

Reports on the simulation work done in the area of the single intersection. Describes the steps in developing a simulation model and the manner of representing traffic in the computer. A report on simulation of a signalized intersection model is included covering 100,000 hours of simulated real-time.

31. Gerlough, D. L. and Wagner, F. A., "Simulation of the Network," Proceedings of the Conference on Traffic Surveillance, Simulation and Control, September 14-15, 1964.

One of a group of papers on various aspects of simulation. It briefly describes the operation of the TRANS model for network simulation. Testing of the model is also described. Comments by Mr. Gerlough describe possible application areas for simulation models.

32. Watjen, W. D., "Computer Simulation of Traffic Behavior Through 3 Signals," Traffic Engineering and Control, Vol. 6, 1965.

This paper very briefly describes the development of a microscopic model for intersection behavior which is then generalized into a

three signal arterial system.

33. Dart, O. K., Jr., "Development of Factual Warrants for Left Turn Channelization Through Digital Simulation," Doctoral Dissertation, Texas A&M University, January 1966.

This work involves a complete field and simulation study of the intersection area. The simulation model used is a microscopic car-following model. The results are then used to determine volume levels at which it becomes beneficial to provide various types of left turn channelization.

34. St. John, A. D., "Study of Traffic Phenomena Through Digital Simulation," Final Report, Midwest Research Institute Project No. RA-13-P, Kansas City, May 1966.

The main features of and results from a digital traffic simulation are presented. The simulation model, which is based on vehicle dynamics and human factor considerations, was developed to study accidents in the freeway environment. The simulation treats following and overtaking maneuvers including weaving and merging. The results agree well with several types of experimental data.

35. Drew, D. R., Meserole, T. C. and Buhr, J. H., "Digital Simulation of Freeway Merging Operation," Texas Transportation Institute Research Report 430-6, Feb. 1967.

The first part of this report is a discussion of the techniques and procedures commonly used in simulation studies. The second part describes a digital simulation program developed to model the operation of a ramp-freeway merging area.

I. METHODS AND INSTRUMENTATION FOR MEASURING TRAFFIC CHARACTERISTICS

1. Johnson, A.N., "Maryland Aerial Traffic Density Burvey," Highway Research Board Proceedings, vol. 7, 1927.

2. Greenshields, B.D., "The Photographic Method of Studying Traffic Behavior," Highway Research Board Proceedings, vol. 13, pt. I 1933.

3. Forbes, T.W. and Reiss, R., "35 Millimeter Airphotos for Study of Driver Behavior," Highway Research Board Bulletin 60, 1952.

4. Wardrop, J.G., Charlesworth, G., "Method of Estimating Speed and Flow of Traffic from Moving Vehicle." Instn Civ Engrs--Proc vol. no. 1 Feb 1954.

   In order to measure traffic speed and volume, observers in a test car record their journey times, count opposing traffic, and keep tally of overtaking and overtaken vehicles. This method has become known as the "moving vehicle method". Practical application of this method and errors occurring in practice are presented.

5. Mueller, E.A., "Recent Speed and Delay Instruments." Traffic Eng vol 25 no. 3 Dec 1954.

   Review of devices for use in traffic engineering such as recording speedometers, apparatus for statistical analysis of vehicle operation, electric counter boxes, etc.

6. Berry, D.S., and Van Til, C.J., "Comparison of Three Methods for Measuring Delay at Intersections." Traffic Eng vol 25 no. 3 Dec 1954.

   Results obtained using a specially constructed delay meter, a sampling method, and a spaced serial photo method are presented and compared.

7. Solomon, D. "Accuracy of Volume-Density Method of Measuring Travel Time." Traffic Eng vol 27 no. 6 Mar 1957.

   Determining effectiveness of traffic control measures at intersections; at usual intersection, travel time may be measured to within accuracy of 5 to 10%; only 1.2 man-hour of field and office time are required to

to measure travel time on single intersection approach during one hour, required equipment included pencil, paper, hand counter, and wrist watch.

8. Wohl, M., "Vehicle Speeds and Volumes Using Sonne Stereo Continuous Strip Photography", Traffic Engineering, Jan. 1959.

9. Wohl, M. and Sickle, S.M., "Continuous Strip Photography - An Approach to Traffic Studies," Traffic Engineering, July, 1959.

10. Ellson, P.B., "Queueing-time Indicator for use in a Moving Vehicle." Instrum. Pract., 13 (7), 1959.

This paper, which was prepared at the Road Research Laboratory, Harmondsworth, described and illustrates apparatus for assisting observers to measure and analyze journey-times at intersections. The observer is provided with a small panel on which the journey log-sheets are held; push-buttons on the panel are pressed at each stop and start of the vehicle while it is queueing and a change-over switch is operated as each new section of the route is entered. The required queueing-times and journey-times, which are indicated by electric digital registers set in the panel, are copied directly onto the log-sheets and the registers are then reset to zero. The indicator consists basically of a half-second contactor clock which gives electrical impusles that are fed into the register. Full details are given of the electrical equipment.

11. A Traffic Analyzer: Its Development and Application", Taragin, A., and Hopkins, R.C., Public Roads, Vol. 31, No. 5. Oct. 1960.

This article gives a detailed explanation of an electronic instrument called the Traffic Analyzer. Originally developed in 1948, numerous changes were made and studies were made with 24 state highway departments, city and county authorities, and a number of universities. These studies ranged from simply obtaining speeds of all vehicles simultaneously in four lanes carrying heavy traffic volumes to very comprehensive studies involving weaving and merging. Special studies were made in Chicago, Detroit, Los Angeles and in several areas in Texas.

A high speed electronic computer was employed to analyze data. Other uses for the analyzer equipment were studies of the effect of traffic operation of various shoulder widths and types, the effect of edge markings on traffic, lateral placement guides for road tests, effect of median dividers on driver behavior and highway capacity and the truck equivalent factor on various highways.

It is felt that future uses of the equipment will involve checking of manual, photographic, and other traffic recording techniques. It is also reported that additional units featuring radical changes in design are presently being developed.

12. Auer, J.H., Jr., "A System for the Collection and Processing of Traffic Flow Data by Machine Methods." Highway Research Board Bulletin 324, 1962.

13. Tamburri, T.H., "California's Aerial Photography Inventory of Freeways," Paper presented at 42nd Highway Research Board Meeting, Jan., 1963.

14. Rice, J.F., "Adoption of Aerial Survey Methods for Traffic Operations," Paper presented at 42nd Highway Research Board Meeting, Jan., 1963.

15. Wagner, F.A., Jr. and May, A.D., Jr., "The Use of Aerial Photography in Freeway Traffic Operations Studies," Paper presented at 42nd Highway Research Board Meeting, Jan, 1963.

16. Wooton, H.J., "Collecting and Analysing Traffic Data Automatically." Traffic Eng & Control vol. 4 no. 10 Feb. 1963.

The paper describes a method of collecting information concerning flow, speed, acceleration, class, direction and headway of vehicles from time pattern a vehicle creates in crossing two closely spaced detectors. Calculations were analyzed using Ferranti Pegasus electronic computer.

17. Howes, William F., "Photogrammetric Analysis of Traffic Flow Characteristics on Multilane Highways," Purdue University, July 1963.

18. Edholm, S. and Kolsrud, B., "Measuring Journey Time by a Photographic Method." Svenska Vagforen, Tidskr., 1963. (In Swedish).

A method is described for studying traffic passing along a short road section. Two cameras, placed at each end of the section, photograph both the passing vehicles and a clock which shows the time in tenths of a second. A slow vehicle is photographed every time one of its wheels passes a pneumatic detector which is laid diagonally across the road; fast vehicles are only photographed once. From the film, information such as registration number, driving direction, vehicle type, and times of entering and leaving the section, is transferred to punched

cards. The information can be used for calculating traffic flow, vehicle density, journey times and speeds, number of overtakings and meetings, and for studying queues.

19. McCasland, Wm. R., "Comparison of Two Techniques of Aerial Photography for Application in Freeway Traffic Operations Studies", Texas Transportation Institute Report, Project 2-8-61-24, March 1964.

The two techniques of aerial photography described and analysed are some stereo continuous strip photography and conventional aerial photography with overlapping pictures. The data collection and reducting techniques are described and the results compared with that obtained by a ground-based observer.

20. Christensen, A., and Hewton, J. T., "Developments of Conventional Ground-Based Detectors," Proceedings of the Conference on Traffic Surveillance, Simulation and Control, Washington, D. C., Sept. 1964.

21. Zupanick, J.E., "Vehicle Classification Sensors for Automatic Traffic Control", Proceedings on the Conference on Traffic Surveillance, Simulation and Control, Washington, D. C., Sept. 1964.

22. Norder, H. "Proposed Research in More Sophisticated Ground-Based Detectros," Proceedings of the Conference on Traffic Surveillance, Simulation and Control, Washington, D. C., Sept. 1964.

23. Jordan, T.D., "The Sky Count Program for Highway Systems Management," Proceedings of the Conference on Traffic Surveillance, Simulation and Control, Washington, D. C., Sept. 1964.

24. Forbes, T.W., Mullin, J.J., and Simpson, M.E., "Traffic Data Acquisition from Air Photos by Modified Conventional Methods," Proceedings of the Conference on Traffic Surveillance, Simulation and Control, Washington, D. C., Sept. 1964.

25. Morrison, H. "The Electronic Computer as an Aid to Traffic Data Acquisition", Proceedings of the Conference on Traffic Surveillance, Simulation and Control, Washington, D. C., Sept. 1964.

26. Baggott, T.A., "Traffic Data Acquisition from Aerial Photographs by Photographic Image Processing", Proceedings of the Conference on Traffic Surveillance, Simulation and Control, Washington, D. C., Sept. 1964.

27. Frank, J. D., "Traffic Data Acquisition from Aerial Infrared Imagery", Proceedings of the Conference on Traffic Surveillance, Simulation and Control, Washington, D. C., Sept. 1964.

28. Buhr, J. H., Drew, D. R., Wattleworth, J. A., and Williams, T. G., Texas Transportation Institute Research, Report 430-1, Dec. 1966.

This paper introduces the research project entitled "Gap Acceptance and Traffic Interaction in the Freeway Merging Process" which forms a part of a four-year program on freeway merging undertaken by the Bureau of Public Roads.

Field studies for the collection of data were performed on a nation-wide basis at a number of selected entrance ramps, utilizing an aerial photographic technique. This Technique, the data reduction methods and the study sites selected are described in detail. Data editing routines and the analysis of the data for basic traffic parameters are discussed and some of these parameters used to illustrate the merging operation at each study site. The qualitative effect of various geo-metric elements on the operation as mirrored by the traffic parameters of volume, density, speed and acceleration noise are discussed.

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