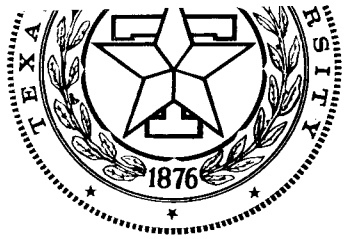

TEXAS TRANSPORTATION INSTITUTE

TEXAS HIGHWAY DEPARTMENT

COOPERATIVE RESEARCH

Theory of Traffic Flow Supplement
2-8-54-1

in cooperation with the
Department of Commerce
Bureau of Public Roads

BIBLIOGRAPHY 67-6

SURVEY OF LIBRARY FACILITIES PROJECT

THEORY OF TRAFFIC FLOW SUPPLEMENT

1. Could Railway Organizing Standards and Mainly Railway Traffic Ruling Methods Be Usefully Applied To Road Traffic? G. DeRosa Transporti Publici (Ministero Transporti e dell'Aviazione Civile, Poazza della Croce Rossa, Rome), Vol. 23, No. 1 pp 29-35. Jan. 1966. (In Italian), Highway Research Abstract Oct 1966 Vol. 36 p. 4.

   Because of the increased volume of traffic, the greater size and weight of trucks, and the higher speeds, serious consideration must be given to the coordination and regulation of the traffic flow. A guide for such regulation may be found in railway organization. Signaling systems, speed, and traffic control have been standardized by railways for many years. Criteria for handling large volumes of traffic moving in several directions and at varying speeds have been established. Many aspects of this control could readily be adapted to high speed freeways.

2. Application of Motor Carrier Continuous Traffic Study Techniques to Assembly of Intercity Freight Traffic Study. Hoy A. Richards and James D. Jones, Texas Transportation Institute, Paper to be Presented at HRB 46th Meeting, January 1967.

   The motor carrier Coninuous Traffic Study makes available certain statistical information which provides reliable estimates of specific operating characteristics for large groups of motor carriers operating within and between given geographic regions of the United States. Experience gained from the development and institution of a CTS in the Southwestern Region suggest that modification of these studies will provide reliable traffic flow data for use in transportation planning and research.

   Certain traffic-flow analysis reports have been compiled from a stratified random sample of approximately 90,000 sampled freight bills. The sample was drawn from the files of the Southwestern Region CTS study carriers and is representative of a universe of 20 million freight bills prepared by these carriers during the year 1965. In addition to a descriptive analysis of intercity freight traffic movement between metropolitan areas, these reports also provide coefficients which are useful in estimating total movements of goods by common carriers of general commodities between specified standard metropolitan areas.

   The data collected provide controls for reporting specific traffic flow characteristics by commodity classification, weight brackets, mileage categories, number of vehicles used, type of rate, etc. Further development of methods used in the CTS should produce a "family" of reports for use in traffic-flow analysis.

Properly designed and interrelated continuous traffic studies, including statistically selected motor carriers from all regions of the United States, will provide reliable information for estimating traffic flow between selected population centers, industrial areas, and marketing regions of this country.

3. Some Aspects of Reverse-Flow Freeway Design, Donald R. Drew, Texas Transportation Institute, Paper to be Presented at HRB 46th Annual Meeting, January 1967.

Designers are reaching a point where they can no longer hope to accommodate projected traffic demands with conventional freeway designs. The problems are not enough freeway capacity and not enough merging capacity with both problems being aggravated by severe unbalances of flow during the peak hours.

When the directional distribution of traffic on a multilane highway is greatly out of balance during peak hours, the capacity of a given section can be appreciably increased by devoting more than half of the lanes to the predominant direction of flow. This principle of reverse-flow operation is grudgingly being applied to freeway design with limited success.

This paper is a generalization of the reverse-flow freeway concept in that it suggests some interchange designs which enable ingress and egress directly to and from the atgrade street system rather than with the outside freeway roadways. In addition to preserving the increased capacity of the reversible freeway lanes, this innovation should double or triple the merging capacity at certain interchanges.

A step-by-step procedure for utilizing this new type of reverse-flow facility is explained. The geometrics of the proposed interchanges are discussed in detail--complete with a plan-profile, typical section, and proposed signalization phasing plan.

4. Spacing of Interchanges and Grade Separations on Urban Freeways, Gilbert T. Satterly, Jr., University of Michigan, and Doanld S. Berry, Northwestern University.

The selection of suitable spacings of interchanges and grade separations for urban freeways was considered as a systems problem. Two objectives were (a) to develop and test a model for comparing alternative spacings of interchanges and grade separations, considering system-wide effects of different spacings; and (b) to determine the sensitivity of the optimum spacings to changes in values of input parameters.

A theoretical grid network of arterial streets speced one-half miles apart with collector streets at one-fourth mile and a grid

network of freeways spaced four miles apart was considered at one-fourth mile and a grid network of freeways spaced four miles apart was considered as one system. Thirteen variations of this system were studied, utlizing spacings of interchanges of ½, 1, 2, and 4 miles, and spacings of grade separations of ¼, ½, 1 and 2 miles.

Vehicular trip data for Chicago obtained from a 1956 origin and destination survey were used as common input for all networks Trip destination densities considered averaged 23,000 and 11,000 trip destinations per square mile with population densities averaging 21,000 and 10,000 persons per square mile, respectively. A level of service was assumed for each functional classification of highway. A minimum time path, all-or-nothing uncapacitated assignment was made on a computer for each of the networks.

Each network was then designed to accommodate the assigned vehicular volumes at the assumed level of service. Cost estimates were made. Annual capital costs and user costs for each network were calculated.

Using the criterion function of minimizing the annual transportation cost for the design year, the optimum spacings of interchanges and grade separations were selected. A sensitivity analysis was also performed to evaluate effects of changes in the input parameters.

For this type of grid system, with constant travel demand, the following conclusions were drawn:

1. The proportion of travel via freeway decreased with increases in interchange spacings.
2. The optimum spacing of interchanges and grade separations is, in general, not sensitive to changes in amortization periods, levels of service, or right-of-way costs.
3. The optimum spacing of interchanges and grade separations is sensitive to changes in time costs and interest rates. As values and grade separations decrease. The general effect of increasing the interest rate is to cause the change in optimum spacings to take place at a higher time cost.
4. If the 4-mi spacing of interchanges is excluded, the range in total annual transportation costs for systems with different spacing of interchanges and grade separations was very low (generally 2 or 4 percent).

Thus it is recommended that other factors be considered along with economic analysis when selecting optimum spacings of interchanges and grade separations. When considering these other factors along with the economic analysis a 1-mi spacing of interchanges with a ½-mi spacing of grade separations is recommended for the higher

trip destination density considered. For the lower trip destination density of a 2-mi spacing of interchanges with either a 1-mi or ½-mi spacing of grade separations is recommended.

5. Operational Effects of Some Entrance Ramp Geometrics on Freeway Merging, Joseph A. Wattleworth, Johann H. Buhr, Doanld R. Drew, Frank Gerig, Jr., Texas Transportation Institute., Papers to be presented at HRB 46th Annual Meeting, Jan. 1967.

Time-lapse, aerial photographs were taken at 29 entrance ramps in seven cities across the country and data from 23 of these entrance ramps are presented. The ramps included in the study had a wide range of geometrics, i.e., acceleration lane lengths 240 ft to 1,500 ft and convergence angles between 1 and 14 deg. The geometric elements for which the operational effects were most carefully evaluated are acceleration lane length, angle of convergence and ramp grade.

Operational characteristics examined were speed of ramp vehicles at the ramp nose and at the merge point, change of speed of ramp vehicles between the ramp nose and the merge point, the relative speeds of vehicles at the ramp nose and the point, the accepted gap number and the distribution of points of entry onto the freeway. All of these analyses were made during periods in which the freeway operating speed was in excess of 40 mph.

Each of the variables, acceleration lane length, angle of convergence and ramp grade, were found to have a great effect on the merging operation. General conclusions regarding entgance ramp design are presented.

6. Statistical Modeling of Travel Speeds and Delays on a High Volume Highway., Theodore B. Treadway, Pennsylvania Department of Highways. and Joseph C. Oppenlander, Purdue University, Paper to be presented at HRB 46th Meeting, Jan. 1967.

This investigation was part of a project designed to evaluate the effectiveness of traffic engineering applied to problems of traffic movement on the US 52 bypass in Lafayette, Ind. The specific purposes were to determine the significant factors which influence travel speeds and delays and to develop statistical models for the estimation of these travel characteristics.

The movements of traffic on the highway were classified as uninterrupted flow between intersections and as interrupted flow at the signalized intersections. Factor analysis and multiple linear regression techniques were applied to express overall travel speeds and delays as functions of factors and variables that were descriptive of the traffic stream, roadway geometry, and roadside development.

The most significant factors in accounting for the variations in travel speeds of uninterrupted flow were the types of roadside development (commercial, urban, and rural) and stream friction. Vehicular delays at traffic signals were largely dependent on the signal timing, traffic volume, and the change of whether or not stops occurred.

7. Color to Combat Road Traffic Chaos--Roads with Directional Strips, Kommunaler Strassenbau (Chausseestrasse 72, Berlin 65, Westsektor, Germany), No. 5, pp 69-71, 1965 (In German) Road Documentation International Road Federation, No. 3, p. 11, 1965.

Permanently colored roads and expressways would help to regulate traffic by giving better directions. They would also increase safety and reduce accidents. The experience gained from the continuous use of the first experimental colored road in Germany during more than a year has been conclusive. Traffic can be directed to different lanes without the usual multiplicity of signals. This new direction has various possibilities: for example, on access roads to highways or on routes through towns.

8. Analysis of On-Ramp Capacities by Monte Carlo Simulation, Robert F. Dawson and Harold L. Michael, Respectively, Assistant Prof. of Civil Engineering, University of Vermont; and Associate Director Joint Highway Research Project, Purdue University, Highway Research Record No. 118, pp 1-20.

In recent years thousands of miles of freeway-type highways have been constructed to provide for the safe, convenient and efficient transportation of persons and goods. Access to these facilities is provided by on-ramps designed to merge ramp traffic into the high-speed, high-volume traffic stream. The efficiency of traffic movement on freeways, and the extent to which the potential capacity of freeways can be realized, depends in part on the adequacy of the access facilities. Improperly designed entrances limit the volume of traffic that can use an expressway and generate congestion that often extends back onto the local system.

9. John D. C. Little and Brian V. Martin, Respectively, Sloan School of Management and Department of Civil Engineering, Massachusetts Institute of Technology; and John T. Morgan, The Australian National University, Canberra City, A.C.T.

Traffic signals can be synchronized so that a car, starting at one end of a street and traveling at preassigned speeds, can go to the other end without stopping for a red light. The portion of a signal cycle for which this is possible is called the bandwidth for that direction. Ordinarily the bandwidth in each direction is single, i.e., is not split into two ro more intervals within

a cycle. Two problems are solved for this case: (a) given an arbitrary number of signals along a street, a common cycle length, the green and red times for each signal, and specified vehicle speeds in each direction between adjacent signals, synchronize the signals to produce bandwidths that are equal in each direction and as large as possible; and (b) adjust the synchronization to increase one bandwidth to some specified, feasible value and maintain the other as large as is then possible. The method of calculation has been programmed for a 20K IBM 1620.

10. Lag and Gap Acceptances at Stop-Controlled Intersections, Per Solberg and J. C. Oppenlander, Respectively, Graduate Assistant and Assistant Professor, School of Civil Engineering, Purdue University, Highway Research Record No. 118, p. 48-67.

The purpose of this research study was to investigate the lag and gap acceptances 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 sidestreet 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 identical 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 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.

11. An Evaluation of Fundamental Driver Decisions and Reactions at an Intersection. Frederick A. Wagner, Jr., Planning Research Corporation, Los Angeles, Calif., and Washington, D. C., Highway Research Record No. 118, pp. 68-84.

There has been broad interest and increasing emphasis in the development and utlization of mathmatical theories and computer simulation models of traffic flow phenomena. The development and effective application of these new techniques is unalterably dependent on a fuller understanding of the fundamental parameters of vehicle and driver behavior. In this connection, there is no substitute for the measurement and analysis of real traffic behavior under actual operating conditions.

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

1. A detailed examination to determine and verify the characteristics of a 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.

12. Estimating Annual Average Daily Traffic from Short-Term Traffic Counts, Robert L. Drusch, Senior Highway Planning Analyst, Missouri State Highway Department. Highway Research Record No. 118, pp. 85-95.

The purpose of this study was to evaluate a method advocated by the U. S. Bureau of Public Roads for estimating annual average daily traffic from short-term traffic counts and to determine whether existing procedures could be improved with reduced annual cost. This study pertained to rural roads carrying 500 or more vehicles per day.

Some of the first tests were conducted for the purpose of determining the most satisfactory method of grouping continuous counting stations and the computation of mean monthly adjustment factors for each group.

One of the first conclusions was that continuous count stations should be grouped on the basis of average monthly adjustment factors of several consecutive years rather than on the basis of the factors for any single year. It was further concluded that division of the states rural roadways into five groups would be sufficient stratification of annual patterns of traffic volume variation.

Tests were made to determine the relative efficiency of seasonal control counts repeated at various numbers of times per year per location for establishing group assignments of roadway sections and estimating AADT. Tests were made pertaining to seasonal control counts repeated four, six and twelve times per year were 3.6, 3.1 and 1.7 percent, respectively. Comparisons of the results of using various seasonal control counts to indicate group assignment of roadway sections showed no significant difference.

The Missouri State Highway Department is considering the adoption of the Bureau's method of estimating AADT using a 7-day coverage count program and seasonal control counts repeated four times a year per location. It is believed that the eventual annual savings of this method would be approximately one-half the cost of the current program.

13. Computer Model of Driving Behavior: The Highway Intersection Situation, Edwin A. Kidd and Kenneth R. Lughery, Cornell Aeronautical Laboratory, Inc., Highway Research Record No. 118, pp. 96-97.

A Digital computer model of the perceptual, decision-making, and response processes of the driver has been formulated for the highway intersection situation. Including simulated vehicle characteristics, the model presents a simulation of human behavior in a dynamic control task. The model is completely deterministic with the possibility for inclusion of probabilistic functions when desirable. A completely determined process was selected to facilitate the study of the effects of various pertinent parameters.

Figure I is the summary flow chart of the computer model. Each process of this flow chart is further defined by subroutines (as numbered) which provide the detail required for the computer program. The set up block of Figure I provides for inputs of the following parameters which may be varied for a particular run: (a) initial location and velocity of the opposing vehicles, (b) obstacles locations, (c) maximum deceleration and acceleration capability of the modeled driver's vehicle, and (e) pertinent perceptual and decision-making parameters and threshold values.

A parameter study of the foregoing variables was conducted to determine the effects on driver performance and accident or near-accident occurrence. Some of the parameters were more important in determining driving behavior than others. These were (a) how far ahead the driver is considering the consequences of his decisions, (b) the time required for each information process and decision (c) the threshold for perceiving angular velocity, (d) the driver's vehicle velocity and (e) location of the obstacle-to-view. In addition, there were significant interactions among these variables.

This technique of computer modeling of the driver-vehicle combination shows great promise as a method for examining the pertinent factors affecting performance of the driving task. The magnitude of this problem in including relevant and irrelevant perceptual inputs, logic and details of the simulated information processing and decision making and the vehicle characteristics precludes an exclusively experimental approach. A model formulation is essential to further studies in this area. This digital computer model seems particularly suited to the problem, but the real test of the model must come from experimental validation, both of the overall output and of particular aspects.

14. Deterministic Aspects of Freeway Operations and Control, Donald R. Drew, Associate Research Engineer, Texas Transportation Institute, Highway Research Record No. 99, pp. 48-58.

Among the important problems arising from the population exposion is that of congestion. Although this overcrowding manifests itself in virtually every aspect of modern life, nowhere

is it as dramatically exhibited as on our streets and highways. The most vigorous attempt to eliminate as on our streets and highways. The most vigorous attempt to eliminate traffic confestion was the development of the freeway, a concept based on (a) the reduction of vehicle-to-vehicle conflicts, (b)elimination of vehicle-to-pedestrain conflicts, and (c) elimination of delay-producing traffic control devices. Still, practically all major cities are troubled with severe peak hour congestion on newly completed freeways.

Previous studes have shown that a relatively small increase in traffic demand on an already heavily loaded expressway can have a very deterimental effect on the operating conditions for all traffic on the facility. Speeds and volumes are reduced, densities and travel times are increased, and the highway immediately loses much of its efficiency. Theoretically, it seems desirable to either ration of completely deny access to the freeway at certain locations.

The automatic evaluation of freeway traffic flow will be a vital element of any future control system. Research must be directed toward the evaluation of the use of surveillance and sensing equipment, and the simultaneous investigation of those characteristics of traffic flow related to freeway congestion which can be determined and treated by such equipment. The complexities and mainifestations of freeway traffic congestion are inherent in the problem. Traffic inefficiency is reflected in such factors as changes in comfort. These factors are influenced by such additional variables as traffic demand, traffic composition, lane occupancy, highway geometrics and the drivers' desired speeds. Before it can be decided just what level of efficiency is economically feasible, congestion should be tolerated during peak periods, congestion must be defined quantitavely in terms of known and measurable parameters of traffic flow theory.

15. Freeway Level of Service as Influenced by Volume and Capacity Characteristics, Donald R. Drew, and Charles J. Keese, Texas Transportation Insitute, Texas A & M university, College Station Texas. Highway Research Record No. 99, pp. 1-47.

As applied to the traffic operation on a particular roadway, level of service refers to the quality of the driving conditions afforded a motorist by a particular facility. Factors which are involved in the level of service are (a) speed and travel time, (b) traffic interruption, (c) freedom to maneuver, (d) safety, (e) driving comfort and convenience, and (f) vehicular operational costs.

Each of the foregoing factors is somewhat related to all the others. The volume of traffic using a facility affects all of the factors and, in general, the greater the volume, the more adverse are the effects. As the ratio of the volume of traffic on a facility to the volume of traffic the facility can accommodate approaches unity, congestion increases. Congestion is a qualitative term, long used by the general public as well as traffic engineers, which refers to what can quantitatively be defined as vehiclurr density. The end result of an oversupply of vehicles is the formation of a queue of stopped (or "crawling")vehicles at bottleneck locations (a "breakdown" of the operation) such that volumes momentarily drop to zero, leaving only congestion on the facility until a clearout can be effected.

Traffic volumes are known to be continuously variable; even at very low hourly volumes there will be infrequent, short-term occasions when a relatively large number of vehicles will pass a given point. There also are regions on a facility which, due to the geometry, inherently will tend to accommodate fewer vehicles. This implies that bottlenecks do exist and thus the level of service on a given facility mayvary even with a "constant"hourly volume. Bottlenecks may be fixed in space due to the aforementioned geometrical considerations of the facility and thus may be studied at the particular location. Such geometrical aspects as entrance and exit ramps have been studied and evaluated as bottlenecks. It is possible also, however, that the random "bunching" of vehicles at any point in space may result in "bottlenecking" due to the statistically variable nature of streams of vehicles, in which case, the designers should be able to predict such peaking characteristics in order to assure acceptable levels of service.

Basically, congestion will be the direct result of the nature of the "supply and demand" on a facility. The supply, in terms of traffic engineering, has been referred to as capacity; the demand placed on the facility, and can be estimated by origin-and-destination surveys if the times of the desired trips are obtained. It is often futile to measure the flow of traffic on an existing facility with the objective of determining the demand on that facility. About the only relationship between existing volumes and actual demand which can be determined from such measurements is whether the demand is, in fact, as large as the capacity during any significant length of time during a day. In borderline instances, peaking occuring within a peak hour might show where capacity is exceeded by demand for intervals of time less than one hour. Even this feature cannot be exhibited by a traffic system which is so inadequate that it limits (or "meters") the input of vehicles such that the volumes are less than the capacity of the particular facility being studied.

It is possible, in a given system, for more vehicles to enter than the facility can handle, then congestion will result whenever the demand exceeds capacity and the accompanying inefficiency results in fewer numbers of vehicles being accommodated by the facility in a given period of time. It is theoretically true that there is some maximum number of vehicles which can use a facility (1) this "possible capacity" is the volume of traffic furing the peak rate of flow that cannot be exceeded without changing one or more of the conditions that prevails. From this value more restrictive conditions of roadway and traffic conditions are imposed to describe the measure of "level of service" that a given lane or roadway should provide. If the conditions are associated with highways or streets to be constructed at a future date, it is defined as design level of service. If the conditions express prevailing traffic flow conditions, it is designated as operational level of service.

Various volume levels can cause various levels of operating conditions, or levels of service. For any volume of vehicles using a particular facility, there is an associated level of service afforded these vehicles. It is possible that the input of vehicles predetermined, suitable level of service volume. Such operational control procedures are being investigated and seem to offer considerable promise.

Although the use of a design level of service volume has considerable appeal in that it conforms to traditional engineering practice the determination of such a volume, relative to various levels of service, is complex. There are regions on a freeway which are subject to more restrictive vehicular operation, such as in the vicinity of an entrance ramp or exit ramp. Such regions should be considered when determining the design volume of a facility and a knowledge of the operational characteristics and traffic requirements at such locations is necessary for proper planning order to avoid future bottlenecks.

16. Some Considerations of Vehicular Density on Urban Freeways, John J. Haynes, Professor and Head, Civil Engineering Department, Arlington, State College, Arlington, Texas. Highway Research Record No. 99, pp. 59-80.

A widespread urban freeway problem is that of the overcrowding or congestion which results from the peak traffic demands. Work traffic is customarily associated with the peak demand so that for a short time each weekday morning and afternoon many urban freeway sections offer a poor level of service to the motorists.

Although control of freeway traffic is, in itself, a anomaly, it has become increasingly apparent that some regulations or control of the traffic during such critical periods is necessary. Investigations are being made of the effect of metering or restricting input to freeways, and speed advisory signs for the traffic on the freeways are being used and evaluated.

Whatever the control action may be, there is a need for practical, reliable, and efficient information which will actuate or initiate the control measure or measures. Control systems will consist of an input sensor component which will supply the necessary information, a logic component which will translate input information into a course of action, and a control component which will enforce the chosen course of action. An iterative series of the foregoing phases will continuously sample, decide, and act throughout a period when control may be necessary.

Surveillance systems combine the first and part of the second components of a control system. These systems can be thought of as preludes to control systems. A television surveillance system uses television cameras and pictures as the sensor component and human beings as the logic components. Traffic stream element detector systems are also used as surveillance devices. Electronic vehicle and speed detectors are used in typical element detector systems as a part of the logic component.

Although traffic stream element surveillance systems have the obvious limitation of not showing all of the traffic situation, they can be better adapted to an automatic control system. Until the present time, only the time-based elements of the traffic stream have been utilized, or sensed, by these element systems, i.e., volume (veh/hr) and/or speed (mph). It is possible with some of the systems to measure the percent occupancy which is related to density but is a point-obtained value and must be based on a time interval.

In the general traffic stream equation, $q=kv$, q is the flow (or volume) in vehicles per unit of time, v is the space-mean-speed of the vehicles in the traffic stream in distance per unit of time, and k is the concentration (or density) of vehicles in a length of roadway in vehicles per unit of length. If any two of these three traffic stream elements are known, the third is uniquely determined. Density, or concentration, has generally been considered the dependent element because the other two elements have been the measured elements. There is, however, no single dependent element but only a relationship between the elements. It is helpful in visualizing the basic traffic stream equation to consider the surface repreeenting the equation plotted on mutually perpendicular axes (fig. 1). The locus of all possible points is a surface which is infinite in extent; however, there are practical limitations which have been rather well established by many previous studies.

Congestion is a qualitative term which is used in traffic engineering to indicate a condition of traffic and traffic movement. Density is the quantitative measure of congestion and, thus, should be the most desirable element to use in freeway operation control. High volumes of traffic or high average speeds are not objectionable from an operational standpoint. Actually, high volumes and speeds are desirable in themselves, but it is known that sustained high

volumes can lead to lower speeds and hence, high densities or concentrations of vehicles on the roadway, which are undesirable. Unfortunately, continuous densities have not been directly measurable. Volumes and speeds have been measured for many years by a variety of means.

Some of the factors influencing the interrelationship of density volume, and speed are the methods of measuring each. Density is, by its very nature, a space element of the traffic stream; volume, is a time-point (nonspatial) element; speeds are sometimes point elements (spot speeds or instantaneous speeds) or are sometimes based on travel times over a finite, short distance (space-mean-speeds). Sensing devices have been used to determine speeds and volumes at a point (1) (or over a very limited length of roadway), and density have been rapidly approximated at short intervals, by electronic means, on the basis of such point information. This process, in effect, extrapolates speed and volume information obtained at a point to density over a distance of up to 1 mi. Density fluctuates continuously and becomes critically high in certain spaces on a freeway in connection with the creation of bottlenecks. Investigations by Keese, Pinnell, and McCasland (2) have shown that traffic in the near vicinity of entrance ramps become congested enough to reduce speeds as much as 50 percent or more during regular peak flow points. From the fundamental relationship, volume is equal to density times speed, it is obvious that if a given volume of vehicles slows down, the density must increase, resulting in more congestion.

It would be desirable to sense density directly over a given length of roadway. From a control standpoint, it is hypothesized that density sensing offers greater promise than the current methods of computing density on the basis of speed and volume information.

If by some satisfactory means density were sensed, there would remain the problem of determining the proper locations of sensors, the required lengths of roadway to be sensed for density, and the critical density values to be used for the controlled operation of freeway traffic. The characteristics of density must be carefully studied by themselves before density is used as a control element. Because density has been the dependent or calculated element heretofore, little has been developed which would enable the study of the basic nature of density.

17. Ramp Freeway Terminal Operation as Related to Freeway Lane Volume Distribution and Adjacent Ramp Influence, Joseph W. Hess, Highway Research Engineer, U. S. Bureau of Public Roads, HRB Record No. 99, pp. 81-116.

This report is 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, a project sponsored jointly by the Highway Research Board and the Bureau of Public Roads. It also contains an analysis of considerable data collected in a 1963 nationwide study of weaving areas by a crew of Bureau of Public Roads junior engineers.

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 level, the freeway as a whole will be operating free-flow. 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. Once the lane 1 volume if determined upstream from an on-ramp, it is possible to determine the allowable ramp volume which in combination with the lane 1 volume will meet a specified service volume for the merge. At off-ramps, the lane 1 volume is that calculated upstream from the exit point, before divergence takes place. Thus, it is possible to forecast when overloading will occur on a section immediately upstream from an exit ramp, given certain freeway and exit ramp volumes.

Seventeen nomographs, derived from the equations, are introduced to provide a fast graphical solution to design and operational problems. Volumes ranging from below practical capacity up to possible capacity can be handled. This makes possible the solution of problems at different levels of service at the administrator's or designer's discretion.

Auxilliary lane usage between on- and off-ramps is discussed and a method of capacity analysis is illustrated with a sample problem. Curves are used to give the cumulative percentage of ramp vehicles on and off the auxiliary lane, related to the distance traversed.

Two-lane on-ramp operation is analyzed from the standpoint of the multiple merges taking place. Two-lane off-ramps are analyzed to show the ramp lane volume distribution and the diverging volume movement which takes place as off-ramp vehicles leave the main traffic stream at the ramp nose. The contribution of the decerleration lane to capacity and smooth operation is stressed.

While data on major fork operation were very sparse, one equation was derived to enable forecasting of lane volume distributions upstream from a diverging major fork where three lane split into two, two-lane roadways.

Finally, preliminary results are given of on-ramp vehicle freeway lane usage studies made in Detroit on the 6-lane Edsel Ford Expressway. On-ramp vehicles were traced downstream after merging by means of the "lights on" technique. Analysis indicates that a stabilization of lane usage percentages occurs at approximately 6,000 feet downstream from the on-ramp nose, with 20 percent of the ramp vehicles in lane 3 at this point, 40 percent in lane 2 and 40 percent in lane 1.

18. Freeway Fatal Accidents: 1961 and 1962, Roger T. Johnson, Traffic Department, California Division of Highways. Highway Research Record No. 99, pp. 117-137.

Accidents and fatality rates for 1961 and 1962 for freeways are compared to those of conventional highways and streets in California. In 1962 there were 426 fewer people killed in California traffic accidents than there would have been if all travel had taken place on conventional highways and streets. For a given amount of travel, there are a little over one-half as many people killed on freeways as on other roads and streets.

The freeway fatal accident rate rose from 2.29 in 1961 to 2.71 in 1962, and the fatality rate rose from 2.70 to 3.35. Ten county routes, amounting to 175 mi. accounted for 90 percent of the statewide increase in fatal accidents, but the accident rate, including nonfatal and property damage accidents on these sections, rose only slightly.

19. Effect of Traffic Volumes and Number of Lanes on Freeway Accident Rates, Richard A. Lundy, California Division of Highways. Highway Research Record No. 99, pp. 138-156.

Three years of experience on 659 mi of four-,six-, and eight-lane freeways have revealed that the accident rates for each classification will normally increase with an increasing ADT. The rate of increase per 10,000-veh increase in ADT is four-lane, 0.240 accidents/MVM; six-lane, 0.094 accidents/MVM; and eight-lane, 0.078 accidents/MVM. For any given ADT, the four-lane freeways have a higher accident rate than the six-lane, and six-lane freeways have a higher rate than the eight-lane. Therefore, as the ADT increases, the difference in rates between the three classifications becomes greater. This relationship introduces the possibility of significantly reducing the total number of freeway accidents by increasing the number of traffic lanes, even though the increase is not required by traffic volumes.

20. Comparative Freeway Study, John Vostrez and Richard A. Lundy, California Division of Highways, Highway Research Record No. 99, pp. 157-199.

Thirty-three sections (220 mi) of freeways with widely divergent accident rates were analyzed. A total of 11,384 accidents were included. These accidents occurred during the course of 9,198 million vehicle-miles (MVM) of travel. The average accident rate for the 33 sections is 1.24 accidents per MVM. The accident rates for the individual sections range from 4.52 to 0.60 accidents per MVM.

The primary purpose of the first part of the study was to obtain information concerning freeway design characteristics as related to accident frequency. The emphasis is on the relative safety value of the various design features. Human factors were considered homogenous throughout the sections unless they obviously played as unusual role in a section's accident history. The second part attempted to analyze each section and explain why that section had an unusually good or poor accident history.

21. Study Techniques for Planning Freeway Surveillance and Control, Joseph A. Wattleworth and William R. McCasland, Respectively, Assistant Research Engineer and Associate Research Engineer, Texas Transportation Institute, Highway Research Record No. 99, pp. 200-223.

Four study techniques, found to be quite useful in planning the peak period freeway surveillance and control activities on the Gulf Freeway in Houston, are presented: (a) entrance ramp origin-destination studies, (b) input-output studies of closed freeway subsystems, (c) aerial photography, and (d) input-output studies of critical intersections in the study area. Data from these studies can be used to plan peak period ramp controls because the demand and capacity can be estimated at each bottleneck (both on the freeway and on the frontage roads and streets) and to plan arterial street controls to provide for diverted traffic because the travel patterns of freeway interchange traffic can be determined. The duration and severity of control at each ramp which are required to prevent congestion, can be estimated. The data are also useful in before-and-after comparisons.

22. Effect of Grades on Service Volume, Leonard Newman and Karl Moskowitz, Assistant Traffic Engineer, California Division of Highways, HRB Record No. 99, pp. 224-243.

The problem of determining effects of trucks on any slow-moving vehicle on the operating characteristics of a section of multilane road is discussed. The action of trucks in reducing the service volume of a road is described and is related to the number of trucks, speed of trucks (steepness of grade), and length of grade. Relationships between these factors are developed and presented in the form of a proposed design chart for determining equal service volumes which would be suitable for rural conditions for any combination of grade, autos, and trucks. The use of this chart in determining when additional lanes should be added and the effects of trucks on maximum capacity of a road are described.

23. Study of Operational Characteristics of Left-Hand Entrance and Exit Ramps on Urban Freeways, R. D. Worrall, Research Engineer, J. S. Drake, J. H. Buhr, T. J. Soltman, Research Assistants; and D. S. Berry, Chairman; Civil Engineering Department, Northwestern University, HRB Record No. 99, pp. 244-273.

The paper is essentially a companion to an earlier report dealing 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-mi 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 on urban freeways in the Chicago area.

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.

24. Freeway Pedestrain Accidents: 1958-1962, Roger T. Johnson, Traffic Department, California Division of Highways, Highway Research Record No. 99, pp-274-280.

Freeways are not designed to accommodate pedestrians and for this reason most freeway ramps are posted to inform pedestrians that they are prohibited from entering. Dismounted vehicle occupants, persons who drive onto the freeway and dismount from their vehicle for some reason, are not specifically prohibited from walking along the freeway.

In addition, all freeways are fenced to prevent entry by pedestrians, animals, and vehicles. In urban areas, a 6-ft chain link fence is placed along the right-of-way. In rural areas, a 4-ft wire fence is used. Pedestrian barriers consisting of 4-or 6-ft chain link fence are often placed in the median within interchanges areas to prevent pedestrians from crossing the freeways. A cable chain link median barrier, installed on approximately 150 mi of freeway, also serves as a continuous pedestrian barrier and 50 mi of blocked-out metal beam median barrier act as a lesser deterrent.

In spite of fences, signs, and barriers, there are still approximately 55 that are fatal, comprising 13 percent of all freeway fatal accidents.

25. Velocity Thresholds in Car-Following at Night, E. P. Todosiev, Space Technology Laboratories and R. E. Fenton, Ohio State Univ. HRB Record No. 122, pp 94-104.

Car-Following is defined as that phenomenon in which a vehicle follows a lead vehicle which is traveling at an arbitrary speed. If the velocity of the lead vehicle is designated by V_1-V_2. It is the threshold of this velocity that has been investigated. Here velocity threshold is defined as that relative velocity which the driver of the rear vehicle can detect with a 50 percent probability at a given headway for a given headway for a given presentation time. The headway is taken as the distance from the driver's eyes to the rear bumper of the lead vehicle.

This study is concerned with the determination of velocity thresholds under night driving conditions, and is based on the premise that the information available to the driver of the following car concerning the state of the lead car, is primarily provided by the taillights of the lead car. When a relative velocity exists between the two cars, this visual information appears as a change in the visual angle subtended by the two taillights of the lead car and apparent changes in the brightness and area of the taillights. For the presentation times of relative velocity used in this study, the changes in headway were so small that it was assumed taillight brightness and area could be taken as fixed. Hence, velocity thresholds were obtained by considering only the change in visual angle. This, of course, may not be the only cue of consequence in detecting relative velocities, but it is almost certainly a major one.

Velocity thresholds for day time driving were obtained in a previous study (1) in which an automobile simulator was also used.

26. Interchange Ramp Color Delineation and Marking Study, Walter J. Roth, Research Studies Engineer, and Frank DeRose Jr., Acting Engineer of Traffic Research, Traffic Division, Michigan State Highway Department., Highway Research Record 105 pp. 113-125.

At two study locations, color coding was applied to edgemarking, delineation, and signing; blue was used for advance exit signing. Although white coding was applied to the through roadway and yellow to the entrance ramps, evaluation was made only on the blue coding for the exit ramps. Evaluation was based on observations made before and after color installation, with emphasis on erratic driving practices and lane change movements. Night and daytime comparisons were made. Driver interviews were conducted to determine public reaction to the general principle of color coding and a specific device used.

Analysis of the results revealed that channeling of traffic into exiting lanes occurred farther in advance of the exit ramp with a reduction of 30 to 32 percent in erratic driving maneuvers. Public acceptance is indicated by the fact that 90 percent of the motorists interviewed stated they received definite benefit from the color scheme.

27. Merging and Weaving Operations in Traffic, D. W. Knox. Australian Road Research, Journal of Australian Road Research Board (60 Denmark St., Kew, E. 4, Victoria, Aus.) Vol. 2, No. 2, pp 10-20, Dec. 1964. Highway Research Abstracts Vol 35, May 1965 pp. 1-2.

Studies are described of merging and weaving characteristics for motor cars and similar small vehicles operating under Australian conditions. Photographic observations were made at two sites on the Cahill Expressway in Sydney. Automatic operation of the shutter on the 16-mm camera was obtained by use of a solenoid and an electrical circuit. Although the rate of exposure was one frame per second, the apparatus could have been operated at any rate within a wide range. Analysis of individual vehicles, shown in enlarged pictures enabled the measurement of speed, lateral movement, gaps accepted, and time and length to complete a merge or weave. In the cases observed where a deliberate maneuver was made in entering a gap, significant correlation was obtained between the lengths of merges and the speeds of the merging cars. Accurate values of acceptable gaps are calculated for safe and moderate driving.

28. Traffic Research at the National Swedish Road Research Institute, Stig Edholm. Traffic Engineering & Control (34 Ludgate Hill, London E. C. 4, England), Vol 6, No. 5, pp 290-295, Sept. 1964.

A brief presentation of the National Swedish Road Research Institute, and a summary of some researches carried out in its Traffic Department are given. The researches include axle load measurements, vehicle differetating traffic counter, methods of travel-time study, graphical representation in travel-time studies, trafficability of roads, road junction delays, accident frequency at three-way junctions, and traffic densitites. and accident rates.

29. Research on Road Traffic, Gt. Britain, Road Research Laboratory, Dept of Sci, and Indus. Res., London, H. M. Stationery 1965. 505 pp. Available from Sales Section, British Information Services, 845 Third Ave., New York 22, N. Y. $8.40.

This book is the companion volume to Research on Road Safety, published in 1963. It covers the work which the Laboratory has carried out to discover methods and principles which practicing engineers, planners and administrators can use to facilitate traffic flow. The subjects covered include prediction of the amount of traffic on a new road, traffic theory, the capacity of road

systems including intersections, the area needed for traffic in towns, traffic control, the economics of road improvements, some safety aspects of rural roads, and practical methods of measuring traffic flow, speeds, and parking densities.

30. Restoring Freeway Operation After Traffic Accidents, Frank L. Lynch, and Charles J. Keese. Texas Transportation Institute (Texas A & M Univ., College Station, Texas) Bulletin No. 28. N.D. (recd. Feb. 1965). 20 pp.

In cooperation with the Automotive Safety Foundation, the Texas Transportation Institute is conducting research on the effects of traffic accidents on freeway operation. A research project was established to determine drivers' reaction when involved in an accident and to determine areas where possible improvements could be made in reducing the time lost to freeway users due to an accident occurring on the freeway and restricting the flow.

The results of questionnaires and correspondence between the officials of the city police departments indicated that adequate numbers of roving patrol cars tend to reduce the delaying period experienced by freeway users after an accident. Knowledge of street access to the freeway in his district enables the investigating officer to become more efficient in reducing the time required to arrive at the scene. Conditions giving drivers ease of access to communications media for reporting an accident are important in reducing the delaying period. The local freeway driver should be aware of his city's ordinances with respect to freeway driving and procedures governing accidents after occurrence. Leaving a vehicle involved in a minor accident in the traffic lane after the occurrence is a serious problem and further study is needed of appropriate methods of reducing the effect on the traffic stream.

31. Analysis of Experiments on Single-Lane Bus Flow, R. Rothery, R. Silver and R. Herman. Operations Research, Special Transportation Science Issue (Operations Res. Soc. of America, Mt. Guliford and Royal Aves., Baltimore, Md. 21202), Vol. 12, No. 4, pp 913-933. Nov.-Dec. 1964.

The results of a series of experiments carried out to determine the characteristics of single-lane bus flow are reported. Using pairs of buses, theoretical "car-following"models of single-lane traffic flow, shown by previous work to be valid for automobiles, are examined for this type of heavy vehicle and found to provide a good representation of the detailed manner in which one bus follows another. Flow characteristics of buses were also

determined by using platoons of up to ten buses. Both of these approaches, which can be termed microscopic and macroscopic, respectively, indicated that a single lane of buses forms a stable stream of traffic and has an optimal flow of about 1,450 buses/hour at a speed of 33 mph for an expressway-type facility.

32. The Traffic Problem in Towns: A Review of Possible Long Term Solutions, R. J. Smeed. Town Planning Review (Liverpool Univ. Press, Liverpool 3, England), Vol. 35, No.2 , pp. 133-158, 1964.

This paper attempts to review very generally the possible ways of dealing with the traffic problem in towns, a problem made especially difficult by the very rapid rate of increase in the numbers of motor vehicles in use. The present paper approaches the matter in a manner rather different from, and pehaps complementary to, the treatment by Buchanan. Buchanan considered in detail some possible changes in four actual towns, assuming existing types of vehicles, methods of traffic control, and types of junctions. This paper discusses some of the possible changes in these factors and consideres the layout of towns in general. It does not consider particular towns. Each method has advantages and disadvantages and to obtain the maximum benefit, both methods are required.

33. Michigan to Up Safety Measures, Traffic Savety (625 N. Michigan Ave., Chicago, Ill, 60611), Vol. 65, No. 6, p 27,June 1965.

The Michigan State Highway Commission is moving swiftly to increase safety measures throughout the state. "Paper work" has already begun in the Traffic Division and other units to edge mark 290 miles of curves of 3 deg or more on freeways and accentuate these markings with reflectorized delineators, edge mark 3,129 miles of 2-lane highways were studies show the markings would be an asset to safety, illuminate 50 overhead freeway signs at critical operational locations, post "Do Not Enter" and "Wrong Way" signs where appropriate at the base of interchange ramps and emphasize the messages with red delineators to warn drivers who miss the signs, remove all trees within 30 ft of pavement edges, resurface with non-skid material to improve auto "stopability" at intersection areas where pavement has been smoothed, and reflectorize bridge peirs, bridge rails and other obstructions.

Other projects, just as important but less obvious to motorists, will include the stepping up computer analysis of accident causes and altering the design of future freeway and highway cross-sections to make shoulders nearly flat and of future overpasses to eliminate the right-hand pier supporting bridges over freeways.

34. The World's Biggest Traffic Problem, Harry Vaughan. Nation's cities (National League of Cities, 1612 K St. N. W., Washington, D. C. 20006), Vol. 3, No. 11 pp. 8-10, Nov. 1965.

This article discusses solutions to the problem of getting from Washington to New York or Boston. Proposals for rapid rail transit, air-bearing systems and linear propulsion are mentioned. Local commuter transportation is also discussed, with the Urbmobile being recommended. Superhighways for freight trucks only, specially designed automobiles and computer control of highways are among the possible solutions to the present traffic problems.

35. California Tries to Stop Wrong-Way Freeway Entries, Western Constr News (609 Mission St., San Francisco, Calif. 94105), Vol. 40, No. 7 p. 92, July 1965.

The California Highway Commission plans to install 5,000 new freeways signs in an effor to help eliminate accidents from wrong-way entried on freeways. This signing program will cost about $500,000. It has been developed after months of studies by highway engineers of many proposals to eliminate the tragic error of wrong entries. In 1964, 52 persons died in freeway accidents from wrong-way entries, and in addition hundreds of persons were injured. State authorities admit that the marking program will not completely eliminate the hazard of the wrong-way entry on freeways, but they are confident it will reduce the number of errors.

The signs are a two-word message of warning--WRONG WAY-- in white letters on a vivid red reflective background. They will be posted on both sides of all freeway off-ramps near the exit points. The messages will not be visible to drivers proceeding in the right direction.