Chapter 5

## SOME EXPERIMENTS AND APPLICATIONS

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## Contents

## Section

5.1-Introduction
5.1.1-Background
5.1.2-Comparison of Experiments and Applications
5.2-Instrumentation
5.2.1-Photographic
5.2.2-Car Following
5.2.3-Transducers
5.2.4-Recorders
5.2.5-Computers
5.3-Driver Experiments
5.3.1-Forbes' Measurements of Driver Reaction Time
5.3.2-Driving Simulation
5.3.3-Galvanic Skin Reflex Studies
5.4-Car-Following
5.4.1-Forbes' Tunnel Experiments
5.4.2-General Motors Car-Following Experiments
5.5-Platoon Studies
5.5.1-Forbes' Platoon Studies in Pasadena
5.5.2-Port Authority Platoon Experiments
5.5.3-Platoon Flow Through Intersection Traffic Signal Systems
5.6-Continuous-Stream Models
5.6.1-Early Work by Greenshields
5.6.2-Speed Headway Measures by Olcott
5.6.3-Experiments in New York Tunnels Using Fluid Flow Models
5.6.4-Experimental Work by Edie, Foote, Herman and Rothery
5.7-Applying Traffic Theory to Flow Control
5.7.1-Manual Traffic Spacing Experiments of Greenberg and Daou
5.7.2-Instrumented Traffic Spacing by Foote, Crowley and Gonseth
5.7.3-Experiments with Completely Automatic Flow Control System
5.7.4-Traffic Surveillance on the John Lodge Expressway, Detroit
5.7.5—Congress Street Expressway Studies, Chicago
5.8-Applying Traffic Theory to Intersection Control
5.8.1-Dusseldorf's Signal Funnel
5.8.2-Experiments with Pacer System in Detroit
5.8.3-Traffic Signal Control Experiments, Toronto

## References

## Chapter 5

## SOME EXPERIMENTS AND APPLICATIONS

### 5.1 INTRODUCTION

In contrast to the extensive theoretical study of road traffic reviewed in preceding chapters, relatively little scientific experimentation has been performed. Experimentation to evaluate a formal theoretical model has been limited, and still fewer experiments have been made to test a prediction based on such theory by altering the conditions of traffic flow.

The qualifications of "scientific," "theoretical model," and "prediction based on such theory," are necessary to distinguish the experimentation which is the subject of this chapter from the experimentation which has provided most of the present knowledge in the field of traffic engineering. As it exists today, the knowledge which traffic engineers draw upon to solve problems and to design roads is largely empirical knowledge, built up through observations, measurements, and statistical analyses. There is a large body of such experimental knowledge, but that experimentation is beyond the scope of this chapter.

### 5.1.1 Background

The basically empirical approach, relying on collection of large amounts of data and statistical analyses, has not been able to answer satisfactorily many of the most important questions about road traffic: Why does one traffic lane regularly carry twice as much traffic as another before congestion occurs? What causes traffic to move in an accordion-like fashion? Will this bridge be a bottleneck if shoulder widths are reduced to 5 ft ? Even the more powerful tools of scientific analysis, which rely on an interaction between theory and experiment, are challenged by the complexity of the road traffic problem.

It is likely that the answers to these and similar questions will be developed and refined through a high degree of interaction between theoretical and experimental work. Experiments alone have not provided the answers; theoretical work by itself is also unlikely to produce detailed workable answers. Both theory and experiment are needed for the development of a scientific understanding of road traffic. Collaboration and understanding among theoreticians, traffic engineers and roadway operators are essential to advance the solution of road traffic problems.

There are three immediate factors which undoubtedly tend to limit the use of traffic experimentation for scientific purposes. First is the inaccessibility of experimental situations for most traffic theorists. Most of the authors of papers on road traffic theory are mathematicians, physicists and other academicians and researchers who do not have ready contact with road traffic operating agencies.

A second difficulty has been the expense of instrumentation for traffic experiments. Although the expense of instruments to measure and understand road traffic is small compared with the expense of roads to carry traffic, the cost of adequate instruments is excessive in light of funds available for basic scientific research. The third factor which has limited the extent of traffic experimentation for scientific purposes is the time usually needed to reduce data for analysis. A shortage of manpower has made it impossible to obtain full value from experiments conducted for scientific purposes.

Important gains are being made to meet these three major needs: accessibility to an experimental situation, better instrumentation, efficient techniques for data reduction. In addition to increasing interest in traffic theory (this publication is one example),
applications of new operating systems based on road traffic theory can provide theoreticians with permanent laboratories. Great strides are being made in the general field of instrumentation, and improved devices are now becoming available to the traffic researcher. Instruments which furnish data in a form suitable for automatic conversion and processing on electronic computers make possible analysis which would be excessively burdensome if manpower were needed for data reduction.

With these gains, and, more importantly, with increasingly better theoretical work, experimentation is likely to become a more important source of scientific knowledge about road traffic.

### 5.1.2 Comparison of Experiments and Applications

Traffic engineering experiments are conducted in a search for knowledge. However, the primary purpose of an application is to improve a traffic operation.

Due to limited traffic knowledge today, it is probable that all straightforward repetitive applications of road traffic theory will produce important contributions to traffic engineering techniques. Any application will be in large measure a continuing experiment which will at first produce considerable new knowledge.

Although there have been few applications of road traffic theory in the past, those made to date are an important source of knowledge for traffic engineers and roadway operators. Applications of road traffic theory are increasing, and it is likely that still more will be made in the next few years.

With both experimentation and application contributing to traffic knowledge, it is clear that the principal difference between the two is merely the length of time involved.

### 5.2 INSTRUMENTATION

In recent years there has been considerable progress in the development of traffic instrumentation systems for measuring driver behavior and vehicular movement. These systems, which utilize improved equipment and new techniques, have become essential in the study of complex traffic flow problems. This section discusses some of the techniques which have been developed.

### 5.2.1 Photographic

Movie cameras offer a relatively inexpensive way to record a large amount of data, but the manpower needed to convert these qualitative data to numerical form for further analysis is often excessive. Cameras are probably best suited when complex traffic movements must be analyzed by using the speeds and paths of individual vehicles. In such a case, securing this information with other equipment (such as transducers and recorders) would be highly expensive. An excellent camera application for this purpose was made by Capelle and Pinnell (4), who analyzed the capacity of signalized diamond interchanges. They used a $16-\mathrm{mm}$ camera at 10 frames per second. Pictures of interchanges were taken from a truck with a tower 35 ft high. A special projector was used to observe vehicle movements and identify frame numbers.

Greenshields (22), who recognized early the usefulness of photography in traffic study, devised special assemblies which adapted a $35-\mathrm{mm}$ movie camera for pulse operation and included reference data in the field of view.

Pulse operation was achieved by a sole-noid-operated clutch that advanced the spring-wound camera one frame per pulse. Thus, used as a time-lapse camera, less film was required and the camera could be synchronized with the operation under study. For example, shooting at 88 frames per minute, each foot of advance along the roadway made by a vehicle in succeeding frames was equivalent to a speed of 1 mph ; that is, a vehicle that advanced 20 ft in succeeding frames moved at 20 mph . The addition of reference data (such as time, frame number, event) greatly increased usefulness of the camera. However, the photographic equipment available at the time of Greenshields' early experiments required a relatively crude system of external lenses and was limited to use with camera lenses of short focal length.
In 1957, Forbes et al. (16) relied heavily on the ability of a camera to record reference data directly on each exposed frame. They used a $35-\mathrm{mm}$ movie camera specially adapted by a series of internal lenses to display on each frame a variety of information. In their experiment, which is described in Section 5.3.1, they displayed a watch, speedometer, and six lights indicat-
ing various driver actions on the accelerator and brake pedals. The camera, operated at a rate of 24 frames per second inside the third car of a three-car platoon, viewed the position of the first two cars in relation to the third car. Positions of the first two cars were determined by parallax. Films were projected on a grid, and the distance of the first and second cars from the third was determined by comparing the apparent distance between marker lights on each car with the known actual distance. Reduction of data by this means required an excessive amount of labor.

The increasing use of cameras as a study instrument has resulted in the development of highly flexible and precise equipment. A $35-\mathrm{mm}$ camera driven by an electric motor is now available. It can be pulse operated and used for time-lapse photography. The camera also contains an internal data chamber for placing reference information on part of each exposed frame. This equipment has been used for the study of wave action in traffic streams moving over the George Washington Bridge (39).

When mounted in a tower of the bridge and aimed straight down at traffic passing on the roadway below, the camera facilitated studying a number of traffic relationships.

Continuous-strip aerial photography (48, 42,38 ) enables the greatest coverage of ground area for traffic surveys. This technique makes it possible to inventory individual vehicle speeds and densities existing at the time of the flight over a length of roadway. The technique uses a continuous strip of film moving over an aperture at a speed which is synchronized with the ground speed of the plane. Thus the view is "painted" onto the film. Focused onto the film are two views (one on each half of the film), one slightly leading the plane and the other slightly following it. Each vehicle is thereby photographed twice. The offset between the position of the vehicle on half the film and its position on the other half is proportional to the speed of the vehicle. When developed, these two film halves are superimposed through a stero viewer, the offset in vehicle position appearing as a vertical, rather than horizontal, displacement. The vertical displacement can be measured by optical techniques to 0.001 in ., and thus the speed of the vehicle can be determined.

Another aerial photographic technique uses time-lapse photography to determine traffic speeds, flows, densities, etc. An increasing number of applications of this technique is being made, and the principle is being extended for use with high-altitude photography ( $10,000 \mathrm{ft}$ ) capable of covering wide areas with a minimum of distortion.

### 5.2.2 Car Following

Instrumentation developed by Chandler, Herman and Montroll (6) provides the most detailed and precise measure of car following now obtainable. As discussed from the theoretical standpoint in a previous chapter, and from the experimental standpoint in Section 5.4.2, data are obtained by connecting two cars with a wire. The second car is equipped with a reel of fine wire. The end of the wire is fastened to the rear bumper of the lead car, and constant tension is maintained by a slipping friction clutch. The distance at any instant between the two vehicles is measured by the position of the reel through a potentiometer geared to the reel shaft. The relative velocity of the two vehicles is measured through a DC generator tachometer operating off the reel shaft. This generates a signal proportional to the rate at which the reel is supplying or taking up wire. Absolute velocity and acceleration of the following car are measured directly in the following car. These parameters, together with a time pulse and an event pulse, are recorded on a six-channel oscillograph carried in the following car. Analysis of the oscillograph charts requires measuring the displacement of each of the six pens and is time consuming. Although it would be possible to automatically convert these data to digital form for direct analysis on an electronic computer, the equipment to do this is costly.

An excellent application of commercially available equipment for traffic study has been made by Jones and Potts (26) using tachographs. These devices are installed in vehicles and, when driven by speedometer cables, inscribe vehicle speed, distance and engine operation on a wax-coated disc. The disc, marked for time, revolves at a uniform rate. In the Jones and Potts application, the speed trace was used to determine the frequency of changes in acceleration. This parameter is a useful index of the driving quality of a road and of car-following behavior on various roads.

Although not intended primarily for carfollowing studies, a device developed recently by Greenshields (21) provides extensive data on driving behavior by recording the driver's actions in steering, accelerating, and braking. When records are made of the input stimuli to the driver by means of photography or other measurements, studies of driver responses to road and traffic events can be made.

### 5.2.3 Transducers

The ideal detector will be accurate, inexpensive, reliable, easy to install, offer a long and trouble-free life, not drift or require other adjustment, and have no effect on traffic. It does not yet exist; but there is now a great variety of detectors, each of which satisfies some of the mentioned requirements.

Before briefly reviewing the various detectors now available, it might be helpful to consider manual data collection. For short-term surveys, the ease of using manpower to collect data is a great advantage. However, the accuracy of the data, the duration of time over which a person can operate continuously, and the influence a person might have on the traffic being measured should all be considered. Where manpower is required to operate recorders, the fastest response time requires more than $0.1 \mathrm{sec}(45)$.

The detectors most frequently used in traffic experimentation fall into three classes-axle detectors, vehicle detectors, and speed detectors (25). Among axle detectors, the pneumatic tube has received widespread use and is one of the least expensive transducers. Its main drawbacks are low reliability, high maintenance, and influence on traffic behavior. A surfacemounted strip treadle that closes an electrical circuit under the pressure of passing wheels is another inexpensive detector. More rugged detectors operating on this same principle, but enclosed in a frame and embedded in the roadway, are used in toll lanes and are highly accurate. A third unit now being developed, which should have a long life, uses strain gages to measure a minute deflection in a metal plate flush on the roadway surface as wheels pass over.

Particularly where commercial traffic is present, it is difficult to convert axle counts to vehicle counts. As a result, vehicle detectors are being used increasingly. Magnetic
detectors are relatively simple in operation, but are not as accurate as the other detectors discussed here. Probably the most accurate and least expensive vehicle detectors are photoelectric cells. However, these are often difficult to install and are not feasible in many environments. A detector which senses a vehicle when a direct beam of ultrasonic energy is broken may be less susceptible to interference by dirt buildup than photocells, but the need to locate transmitter and receiver on opposite sides of the vehicle poses similar installation problems. This resonant ultrasonic detector should not be confused with another detector which also operates on ultrasonic energy. It measures the time required for a pulse of sound from a transmitter to be reflected back to a receiver located in the same housing. The latter detector is simpler to install and is highly accurate, although more expensive. Several other vehicle detectors are available in the same price range as the pulsed ultrasonic unit. Radar detectors are in widespread use, and present models are quite accurate. A highly accurate vehicle detector, which can be installed relatively easily in pavements, detects vehicles through current flow induced in a loop of wire. The induction loops are also proving to be relatively free of the need for maintenance and adjustment.

Speed detectors are not available in such variety. Radar speed detectors are accurate and reliable, although they require associated logic circuitry. These units measure speed by sensing a Doppler shift in the radar frequency. Ultrasonic units are also available to measure speeds by use of the Doppler principle. A simplified and less accurate approximation of speed has been derived. This method uses ultrasonic detectors which convert the duration of time a vehicle is under the detector into a speed reading by assuming the vehicle is of a particular length. Although vehicle lengths vary considerably, ultrasonic units are available to distinguish autos from trucks and buses by differences in vehicle height. The use of one assumed length for low vehicles and a longer assumed length for high vehicles brings the accuracy of this speed measure to an operationally useful level.

### 5.2.4 Recorders

The multi-pen recorder used extensively in traffic studies offers a low-cost method
of recording many events simultaneously. For experiments in which it is difficult to work with ink, traces can be made on waxcoated or electro-sensitive paper. Reduction of event data generally involves scaling the distance between successive displacements on the trace from each pen and/or relating the displacements with base time through reference to chart speed. Sweep pen recorders are also available with several channels. These record an analog of an input signal, tracing the magnitude of flow, speed, density or some other parameter over a period of time.

To provide a direct numerical record for ease in data reduction, a printing time clock has been used on some applications (12). This device prints time to 0.1 sec , plus a six-letter code, on standard adding machine tape. Hours, minutes and seconds are printed in figures; tenths of a second are printed on a vernier scale. The machine is actuated by switches which key the printing mechanism and select the assigned code for the particular event. This device does not incorporate any means of temporarily storing simultaneous pulses, thus is limited in the number of points which can be recorded at any one time. Even though the direct digital recorder is easier to work with than the multi-pen graph, there is still a large amount of labor required to analyze the record from the time clock device.

An extensive system for recording traffic data has been assembled by the Bureau of Public Roads (43) to analyze vehicle speeds and lateral positions in traffic lanes. Inputs are from two pneumatic or strip treadles laid across the traffic lanes to measure vehicle speeds, and from a third treadle which is segmented to measure vehicle placement. These events are associated with a 100 -cycle-per-second time base, and through equipment mounted in a specially designed truck are punched on a five-channel paper tape for subsequent conversion to punched cards and analysis by electronic computer.
A further breakthrough has been made recently by General Motors with a device which functions similarly to the time clock recorder previously discussed. It provides a punched paper tape output with times measured to the nearest 0.02 sec for automatic conversion to IBM cards (11). Driving this device with a trap of photocells or other
vehicle presence-sensitive transducers, it is possible to determine the time headways, speeds, space headways, relative velocities, accelerations and lengths of successive vehicles passing a point. The device is now being augmented with magnetic tape recorders to permit gathering these data simultaneously at many points on a traffic lane and in adjacent lanes. A simplified version of this clock-tape punch unit has recently been purchased from a data systems manufacturer by The Port of New York Authority and is available for experimentation.

In addition to these graphical and digital recorders, many other recorders have been developed in recent years for all types of experimentation. As with transducers, the traffic experimenter can select among a broad range of instruments to find the one best suited for this purpose.

### 5.2.5 Computers

Increasing attention is being given to devices for traffic experimentation which accept a number of inputs and generate particular output signals depending on the pattern and timing of the inputs. A complete range of analog computers is available to indicate directly the volume, speed and timebased density of vehicles flowing past a point (41). Another manufacturer markets equipment to compute volume and lane occupancy ratio. This equipment is installed for experiments on the John Lodge Expressway in Detroit and on the Congress Street Expressway in Chicago. By immediately assigning values to the principal characteristics of a traffic stream, these devices enable direct experimentation without intermediate data reduction and analysis.
More detailed studies can be performed on more general purpose digital computers using punched paper tape inputs from field recorders or IBM cards punched from manually prepared records. In addition to being a powerful analytical tool permitting the rapid handling of vast quantities of traffic data in complex analyses, the general purpose digital computer also offers great promise as a traffic control component (2, 5). The potential of general purpose computers for contributing to the understanding and more effective control of road traffic is largely untapped at the present time.

### 5.3 DRIVER EXPERIMENTS

It is important to measure driver behavior in response to traffic events when developing a theoretical understanding of road traffic. The driver is one of the key elements in road traffic, together with vehicle, traffic stream, roadway, and roadway environment characteristics. Although considerable attention has been given, particularly in recent years, to measuring driver behavior from the standpoints of safety and accident prevention, relatively little experimentation has been performed for the purpose of understanding how driver behavior determines and affects road traffic.

### 5.3.1 Forbes' Measurements of Driver Reaction Time

One of the most significant experimental studies in the field was conducted by Forbes et al. in 1956 and 1957 (16). Objectives of their research were to determine effects of lighting and other operating conditions on driver reactions, to measure driver perception response relationships which determine acceleration and deceleration rates of successive vehicles, and to examine these factors in relation to other factors affecting driver behavior under various operating conditions.

Their experiment measured the reaction of a driver under various environmental conditions to a set of standard changes in the behavior of cars ahead of him. A platoon of three cars was formed with the driver under observation located in the third car. Control of the experiment was exercised by a passenger in the third car who could signal to the driver of the first car in a manner undetected by the driver of the third car. On signal, the driver of the first car would accelerate or decelerate, and drivers of the second and third cars would respond as though they were commuters on the way home. This experiment was conducted for many third-car drivers and in many different environments.

The speed and driver actions on the accelerator and brake pedals of the third car, together with the field of view observed by the third-car driver, were recorded on film by a specially-equipped camera mounted in the third car (see Section 5.2.1). One of the most interesting findings of the research was that any marked deceleration and acceleration in the platoon increased
time headways between the vehicles. This suggested that traffic flows would be highest when speed changes are at a minimum, an indication which has subsequently been confirmed (45).

The experiment also showed that there is a difference in the reaction time of drivers, depending on the environment in which they must react. On a roadway curving to the right, drivers took longer to react than on a roadway curving to the left. Similarly, downgrades, low illumination, and even subjective constrictions, tended to lengthen reaction times.

The third important finding from these experiments was that the time required for the driver of the third car to react to a deceleration was shorter than that for an acceleration. The theoretical implications of this finding have yet to be fully evaluated.

### 5.3.2 Driving Simulation

It is likely that the Forbes findings concerning driver reaction times can be understood better when it is possible to quantify the information presented to the driver in each of the experimental situations. Presumably, the better informed a driver is, at least up to some point, the better he will be able to anticipate the proper reaction. This area of research should produce much important information for the designers and operators of roadways, and can probably best be undertaken in simulated controlled environments.

Work has been under way in the last few years at the Institute of Transportation and Traffic Engineering in California (24) on the construction of a driving simulator that uses motion pictures to provide visual inputs. Progressive steps are being taken to increase the realism of the projected films, including shooting both front and rear views and projecting them on wide-angle curved screens. The vehicle which the driver operates is mounted on dynamometers and is being equipped to roll and pitch in response to accelerations and projected "road" characteristics.

Another approach has been outlined by the U. S. Public Health Service, using scalemodel terrains over which television cameras would be "driven" by an experimental subject viewing the television monitor. This technique would enable complete control of the environment presented to the experi-
mental drivers, but it apparently is not as close to operation as the filmed input simulator at ITTE.

Another approach has been developed at Ohio State University (44) to investigate the acceleration patterns followed by drivers responding to changes in relative velocity with a car ahead. These researchers used a television camera viewing a model car ahead and, beyond the model, a representation of landscape passing at a controlled velocity.

Distance between the model car and the television camera is controlled by moving the model car in response to acceleration changes initiated by the experimental driver.

An even simpler simulation has been used recently by Michaels and Stephens (32) to study the driver's ability to perform simultaneously a guidance control function while recognizing other information inputs. Such rudimentary simulators are of definite use in studying limited aspects of driver behavior.

Simulators are an especially powerful tool for developing traffic theory because they enable control and precise measurement of nearly all variables in the driving process. The progress being made at ITTE is promising, and further attention in this area will assist greatly in understanding road traffic.

### 5.3.3 Galvanic Skin Reflex Studies

Significant research on human factors is being conducted by the Bureau of Public Roads. Michaels (31) is measuring galvanic skin reflexes of drivers moving in the traffic stream through various environments. His experiments show that driver tension decreases as predictability of interferences increases. A corollary is that driver tension increases as the driving situation becomes more complex.

Measurements of galvanic skin reflex have also been made by Cleveland (7), who found that illumination of a " $Y$ " intersection reduced the tension in drivers traversing the intersection.

### 5.4 CAR FOLLOWING

The theory of car following describes the manner in which one vehicle follows another. This has been used to describe the discontinuity which exists in a stream of traffic when it suddenly becomes congested.

Data derived from many car-following experiments have substantiated the theory, which is essentially a measure of driver behavior.

### 5.4.1 Forbes' Tunnel Experiments

As part of his research to measure driver reactions as a function of environment, Forbes (16) conducted car-following experiments in the Holland, Lincoln and the Queens Midtown Tunnels. These experiments consisted of having the cameraequipped car drive in the regular traffic stream. The driver of the experimental car was instructed to drive in a manner duplicating as much as possible the behavior of the driver in the car in front of him. Thus, when the driver of the preceding car would accelerate, so would the driver in the experimental car.

Inasmuch as the lead car in these experiments was not equipped with reference lights enabling subsequent parallax measurements to determine the difference between lead and experimental cars, these measurements have considerably more error than the measurements taken within the three-car platoons mentioned in Section 5.3.1. Nevertheless, they provide an interesting pattern of driver behavior which is now being analyzed.

### 5.4.2 General Motors Car-Following Experiments

Extensive experimentation has been conducted by Chandler, Herman, Montroll, Potts, Gazis and Rothery (6, 23, 17). Their work is of major theoretical importance and is included in Chapter 2. It will be mentioned here only briefly, but because the work does include experimentation, it is cited as a matter of experimental as well as theoretical interest.
Their experiment consisted of measuring the distance and relative velocity between a leading car and a following car by means of a wire stretched between the two cars (see Section 5.2.2). The take-up reel for the wire was mounted on the front bumper of the following car, and motions of the reel were converted to electrical signals by potentiometer and tachometer. These signals were recorded on a six-channel oscillograph, which was also recording the speed and acceleration of the following car plus the time and special reference points.

Analysis of the oscillograph records presents a difficult problem in data reduction. Only part of the data collected in Detroit and in vehicular tunnels in the New York area has been analyzed. However, even the limited data available shed light on the processes by which one car follows another.

More recently Jones and Potts (26) have used tachographs to measure the dispersion of acceleration noise in car-following studies. These records, although much less precise, are considerably easier to analyze. Section 2.3, on car following, presents the theoretical results of this work which have already been published.

### 5.5 PLATOON STUDIES

Many studies have been made of traffic behavior within platoons to evaluate this effect on traffic flow. Although this work has not been conclusive, it has shown that platoon behavior is of major consequence in the application of traffic flow theory.

### 5.5.1 Forbes' Platoon Studies in Pasadena

Forbes (15) reported in 1951 that traffic behavior within platoons was not adequately described by the behavior of the over-all traffic stream. He based his work on speed, headway and volume studies of traffic on the Pasadena Freeway. Although previous studies of mass traffic behavior reported decreases in speed as traffic volumes increased (and average headway times decreased), Forbes observed that there was little relation between speeds and headways (either time or distance) of vehicles within platoons. These observations identified platoon behavior as an important element in traffic theory, although Forbes did not consider the theoretical consequences of the data in that report.

Defining a platoon member was a major difficulty encountered by Forbes and others who subsequently studied platoon behavior. Forbes reviewed his data in 5 -min classes and considered a platoon member as one whose time headway was less than the mean for that class. At least three successive vehicles with below-average time headways were necessary to constitute a platoon.

### 5.5.2 Port Authority Platoon Experiments

The problem of defining who is a platoon leader and who is a member of a platoon
was avoided in experiments conducted by The Port of New York Authority (10) in the Holland Tunnel South Tube in 1959. In this experiment, the platoon leader was an experimental car traveling at a fixed speed. These experiments to evaluate platoon behavior and measure road capacity were conducted during off-peak periods when normal speed of the traffic stream was higher than optimum (in off-peak periods the speeds in the Holland Tunnel are approximately 35 mph ). Optimum speeds for this tube lie between 20 and 25 mph - that is, at those speeds traffic flows are highest. The hypothesis was that if a platoon of drivers were assembled at random and required to drive behind a platoon leader traveling at a speed close to optimum, the length of the platoon at any point would indicate roadway capacity. In traversing roads of high capacity at this optimum speed, drivers would drive closer together on the average than in traversing a road of lower capacity.

Following the platoon leader, nine cars taken at random entered the tunnel. Ten headways after the first experimental car, a second experimental car was introduced. The time for the two experimental cars to pass any given point in the tunnel (reconstructed from records maintained in the experimental cars) was, therefore, 10 times the average time headway being maintained by the members of the platoon at that point. It was found that the capacity profile of the roadway determined by repeated experiments of this type was similar in pattern to the profile measured in other experiments (see Section 5.6.3). However, the capacity values for this platoon analysis were much higher than those obtained in other measurements ( 1,550 versus 1,250 veh/hr).

In other analyses of Holland Tunnel data Greenberg and Daou (20) observed the tendency for flow to be higher following a gap. This observation was consistent with the results of the optimum speed platoon experiments and suggested that over-all flows might be improved by the periodic introduction of gaps in the traffic stream (see Section 5.7.1).

Characteristics of platoons in the traffic stream passing through the bottleneck in the Holland Tunnel South Tube were examined through extensive measurements made in 1960 by using the General Motors data acquisition system discussed in Section
5.2.4. This system collects data in a form suitable for direct processing by electronic computer, enabling use of quite complex definitions to identify platoons. The definitions used in the published report (11) considered both the extent of space headway available to a vehicle (the particular headway varied with speed) and whether a change in the type of flow had occurred. The latter was manifested by excessive relative velocity, or by a change in acceleration sign (positive to negative or vice versa) for a group of vehicles.

Behavior of the various types of platoons was examined, and it was clear that the highest flows were attained with the highest speed platoon leaders. There did not appear to be a consistent relationship between speed reduction and platoon length or platoon type. However, further analysis of platoon behavior is needed, and theoretical work is under way.

### 5.5.3 Platoon Flow Through Intersection Traffic Signal Systems

Apart from the formation of traffic platoons in continuous flow, the action of signalized intersections in forming, releasing and passing platoons of traffic makes platoon behavior of major consequence in traffic theory. Experimental studies of platoon behavior through signalized intersections have been made by Lewis (28), Pacey (36), Gerlough (19), and Newell (34).

As an example, measurements of platoon dispersal as the vehicles move downstream from a traffic signal were reported by Lewis (28) to compare vehicle-actuated traffic signals with coordinated signals. In the Lewis study the signals in question were 0.81 mi apart on a road with virtually no traffic interruptions between the signals. The analysis showed that coordination of signals at a distance up to 0.65 mi apart would yield better results, because of the platoon behavior, than would be yielded by random operation of the downstream signal.

Applications of platoon studies made by Von Stein (46) and Morrison (33) are discussed in Section 5.8.

### 5.6 CONTINUOUS-STREAM MODELS

For many years researchers have compared the characteristics of traffic flow to
those of a stream of water. Studies based on this comparison have been both statistical and theoretical, describing the wavelike action by which changes in the flow of a few vehicles are transmitted throughout the traffic stream.

### 5.6.1 Early Work by Greenshields

Greenshields (22) reported his observations of vehicle traffic flow in 1934, and suggested a linear relationship between speed and concentration. Thus, on flow-concentration coordinates as concentration increased from zero to jam, flow would rise to a maximum and then fall back to zero on a parabolic path. The form of this relationship is particularly important because it permits inferring the maximum flow obtainable over a short section of roadway from the speed and space headway relationships maintained by drivers at lesser flows.

### 5.6.2 Speed Headway Measures by Olcott

The capacity of a roadway section as determined from speeds and headways of traffic passing through that section at less than capacity flows is of basic importance in locating bottlenecks on uninterrupted roadways and determining the margin of capacity available at non-bottleneck sections. This problem is particularly noticeable in the case of vehicular tunnels which, except for sections of vertical and horizontal curves, are uniform throughout their length. Despite this uniformity, congestion occurs in the traffic stream at characteristic points in vehicular tunnels.

To determine whether the speed concentration relationship proposed by Greenshields would be applicable to tunnel traffic flow, Olcott (35) measured the speeds and headways of vehicles in various points in Queens, Midtown and Lincoln Tunnels. Using 5-min time slices of traffic to compute mean space speeds and mean densities, Olcott ran a linear regression analysis and found that 88 to 97 percent of the variability in traffic speeds was related to change in the density of the stream. The estimates of capacity derived from his analysis were somewhat higher than the maximum flows generally obtained in these tunnels, indicating that the linear speeddensity relationship was not completely applicable.

### 5.6.3 Experiments in New York Tunnels Using Fluid Flow Models

The most significant developments in theoretical descriptions of road traffic as a continuous stream were made in 1955 and 1956 by Lighthill and Whitham (29) and by Richards (40). Their work on hydrodynamic models of traffic flow is discussed in detail in Chapter 1.

Edie and Foote (12) analyzed traffic flows in the Holland and Lincoln Tunnels to evaluate hydrodynamic models as a description of tunnel traffic flow. The hydrodynamic models have provided considerable insight into the behavior of traffic upstream and downstream from bottlenecks. This analogy produces insight particularly into the wavelike action by which changes in flow are transmitted in the traffic stream and is useful in relating flow at the observed point to a restriction at another point.

It is an assumption of the kinematic and similar models that at a given flow less than maximum, traffic would tend to vary around the low concentration or the high one given by the flow-concentration curve and would not fall in between. This assumption permits deductions to be made about flow behavior on each side of the bottleneck which are useful in determining the capacity of non-bottleneck sections. The empirical results showed, however, that traffic flow upstream and downstream does not follow exactly the patterns suggested by the fluid flow analogy. Upstream from the bottleneck, congested flows tended to stretch out over a range of concentrations at a fixed flow level. Downstream from the bottleneck flows tended to assume a small range of concentrations at a fixed speed.

Work by Palmer (37) independently evaluated the application of the Lighthill and Whitham kinematic flow theory for describing traffic behavior on the Merritt Parkway. It was found that the actual observed results conformed quite closely with the results obtained when using the Lighthill and Whitham model.

The hydrodynamic models have been most useful in describing the wave-like behavior with which changes in traffic flow, speed and concentration are propagated through the traffic stream. Experiments conducted in the Holland Tunnel (35) measured these waves and related them to the action of a bottleneck.

### 5.6.4 Experimental Work by Edie, Foote, Herman and Rothery

The Lighthill-Whitham model does not specify a particular form for the flow concentration relationship over the entire range of possible concentrations. Therefore, it is not directly useful in determining capacities from the speed headway relationships observed in subcapacity flows. Richards' model assumed the linear speed-density relationship proposed by Greenshields. Greenberg (20) has suggested a fluid flow model which would specify a continuous relationship over the entire range of densities. Although Greenberg's model appears to fit observed data reasonably well, the observations available at the time his model was formulated were not sufficient to determine whether his model provided more accurate description than previous models. A further refinement was suggested by Edie (39).
More recent experiments by Edie, Foote, Herman and Rothery (11), using an electronic time clock with punched tape output, have provided flow data on 24,000 vehicles through the Holland Tunnel South Tube. This sample provides an empirical basis for defining relationships among flow and concentration, speed and relative speed, and other relationships for both the total stream and for platoons of various types.

### 5.7 APPLYING TRAFFIC THEORY TO FLOW CONTROL

The most significant practical result stemming from application of traffic theory has been an awareness of the importance of maintaining speed to obtain maximum flow through bottlenecks. This awareness was brought about through the application of traffic theory flow control in locating bottlenecks and measuring their capacity.

### 5.7.1 Manual Traffic Spacing Experiments of Greenberg and Daou

The possibility of improving traffic flows by controlling the number of vehicles on the critical road section at any time has been of interest to traffic engineers for many years ( 1,3 ). Attempts prior to 1956 to apply this concept to tunnel traffic flow were not successful. Working with the Holland Tunnel data discussed in Sections 5.5 and 5.6, Greenberg and Daou (20) of the Port

Authority observed that small gaps frequently occurred in the traffic stream when movement was at a high rate and fluid. This suggested that the forced introduction of small gaps might bring about the desired result of maintaining fluid flow and preventing congestion.

To test this possibility, experiments were conducted in 1959 whereby traffic flows entering the fast lane of the Holland Tunnel were limited to no more than 22 vehicles each minute. This was accomplished by an observer who counted the vehicles, observed a stop watch, and signaled a police officer to interrupt traffic for the time between the passage of the 22 nd vehicle and the completion of one minute after the arrival of the first vehicle. Inasmuch as more than 22 vehicles per lane would frequently desire access to the tunnel in a minute, this control caused periodic introduction of spaces in the traffic stream.

Experiments were conducted on alternate days over a six-week period for one hour in the afternoon. The rate of traffic flow increased 6 percent when the control procedure was used.

This improvement was related to the tendency of each successive vehicle in a platoon to travel slower than the vehicle ahead of it as the platoon passed through a bottleneck. A study by Palmer (37) independently reported the same finding.

It has been suggested (10) that as more vehicles enter the critical road section, the space between them is necessarily less and hence platoons become longer. With longer platoons and the average decline in speeds as the platoon lengthens, speeds eventually drop so low that the time required by successive vehicles to pass a point starts to lengthen. When this occurs, vehicles approaching this point must delay arriving at that point, and their sudden slowing precipitates a shock wave back through the stream (as discussed in Section 5.6.3).

The frequent gaps inserted by Greenberg and Daou prevented formation of excessively long platoons and enabled speeds to remain slightly higher than critical.

### 5.7.2 Instrumented Traffic Spacing by Foote, Crowley and Gonseth

Because the manual traffic spacing experiments discussed in Section 5.7.1 were limited to a particular hour, with a flow limit
of 22 vehicles per minute derived from study of traffic behavior in that lane at that time, a new series of experiments was undertaken by Foote, Crowley and Gonseth (14) to extend the application of this procedure.

As the first step, a simple device for spacing traffic automatically was constructed. It consisted of a stepping switch to count vehicles and a one-minute timer. Vehicles were detected entering the tunnel lane. When the pre-set number of vehicles (ranging from 15 to 24) had entered the fast lane of the tunnel in less than a certain time, the device would automatically turn entrance signal lights red, energize flashing "STOP" signs and sound a bell for the remainder of that minute.

Because traffic conditions in the Holland Tunnel vary widely during the week, it was not feasible to think in terms of a predetermined "optimum" setting for the traffic spacer. A means of setting the input control for the particular traffic conditions existing at any one time was considered essential for regular operation. Inasmuch as the immediate purpose of the control system was to prevent traffic speeds at the bottleneck from dropping below critical, it was decided to continuously measure bottleneck speeds and determine the proper setting for the input control based on that information. With slow speeds at the bottleneck, the input control was set to insert frequent spaces in entering traffic.

Experiments were conducted over a sixweek period for three hours in the morning and three hours in the afternoon. An experimenter observing speeds inside the tunnel constantly determined the proper settings for the input control.

Several major improvements were gained when this system was in operation. Traffic production through both lanes of the tube was increased 5 percent during the critical hour, particularly in the afternoon. The increase was caused by both a 25 percent reduction in the occurrence of disabled vehicles and by an improvement in the speed-headway relationships maintained by motorists passing through the bottleneck in the optimal speed range. The modest but significant production increases had a marked effect on traffic congestion awaiting entrance to the tunnel. There was a reduction of 33 percent from three hours of con-
gestion to two hours of congestion, when the flow of tunnel traffic was controlled. Also, there was a sharp reduction in the contamination of tunnel air by vehicle exhausts. When traffic moves at constant speeds, far less carbon monoxide is emitted than in stop-and-go driving.

### 5.7.3 Experiments with Completely Automatic Flow Control System

Another purpose of the instrumented traffic spacing experiments was to evaluate equipment for permanent operation of the flow control system. It was found that the test procedure, relying on an observer to evaluate constantly information on traffic speeds and flows from several sources and then to decide the best setting for the input control, was not fully effective. The continuous concentration required on the part of the observer, the extreme rapidity with which traffic conditions could change, and the number of points which the observer should consider in reaching his decision, all made his job highly demanding. For regular operation, it was concluded that a completely automatic system should be developed.

Based on these experiments, the Port Authority has now developed what might be described as the "first generation" prototype automatic system for controlling traffic flow (13). The prototype system measures speeds at two points in the fast lane of the Holland Tunnel South Tube by means of two sets of photocells, each set bounding a 13 -ft zone. The amount of time required for vehicles to pass through each zone indicates whether they are going faster or slower than a pre-set speed value. The system also measures the number of vehicles passing through the bottleneck at the foot of the upgrade, where one of the sets of photocells is located. During each minute, the system considers the bottleneck flow and determines whether speeds at the bottleneck and approaching the bottleneck are high, medium, or low. Depending on this volume and speed information, the computer then sets the input control for spacing traffic at a certain level for the next minute.

If the speeds are low inside the tunnel, the computer will set the input control at a value lower than the number of vehicles that pass through the bottleneck in the pre-
ceding minute. As long as speeds inside the tunnel remain at a low level, fewer vehicles will be entering the tunnel than passing through the bottleneck. Eventually speeds will rise. When this occurs, the system will allow additional vehicles to enter the tunnel until speeds stabilize in the mid-range. Limited operating experience has been gained with this system, and it appears to be functioning as intended. However, analysis of its results shows that further improvements can be made, and it is expected that development will continue through several additional models. This system is also being extended to other tunnels operated by the Port Authority.

### 5.7.4 Traffic Surveillance on the John Lodge Expressway in Detroit

An extensive test of surveillance and control equipment on the John Lodge Expressway in Detroit is being conducted to evaluate equipment and improve traffic flow. Major steps are being taken to improve flow by the early detection of interruptions, use of lane control and changeable speed signals, and control of traffic entering the expressway.

Reports by Gervais (18) and others indicate that significant improvements in expressway traffic flow can be achieved.

Research is under way on a $3.2-\mathrm{mi}$ section with traffic volumes of more than 160,000 veh/day. Despite overloading, traffic is being handled reasonably well.

Closed-circuit television is one of the surveillance methods. Fourteen cameras, each attached to its own monitor, are so spaced on bridges that pictures of almost all portions of the freeway can be obtained. Special equipment provides a usable night picture and excellent daylight pictures under varying weather conditions.

Research is intended to lead to development of a traffic control system which would utilize information gained from the TV monitoring network.

A recently-installed control system consists of lane signals and variable speed signs. The lane signals are a red "X," to indicate that a driver must leave his lane as soon as it is safe, and a green arrow, which indicates the lane is open for traffic. The variable speed signs permit speed messages in 5-mi increments from 20 to 60 mph . Information from sensing equipment along
the freeway is instantly analyzed to determine appropriate speeds.

The system requires control from a central point with equipment circuitry which changes signals at remote points and then confirms that the signals are operating properly.

An ultrasonic vehicle volume detector also in use is able to detect with reasonable accuracy whether a vehicle is a truck or a passenger car.

Data obtained from this second surveillance system have enabled operators to compute average speed of the traffic stream, average time headway, average distance headway, and average distance spacing.

This project, using television monitoring in conjunction with traffic sensing devices, has produced valuable information for both traffic control and research purposes.

### 5.7.5 Congress Street Expressway Studies in Chicago

A series of vehicle detectors has been installed on the outbound lanes of the Congress Street Expressway in Chicago (30).

A 5 -mi test section includes several onand off-ramps, a transition of four to three lanes, and some apparent bottlenecks. Traffic volume counts and lane occupancy are measured at each detector location. The surveillance project began with a complete inventory of flow characteristics throughout the test section.

Plans are being made to experiment with control measures as possible methods for limiting congestion and maintaining traffic flows at maximum capacity level.

The project is designed to conduct operational studies, locate critical points, determine causes of congestion both qualitatively and quantitatively, investigate ways to improve flow, and measure the resulting benefits to traffic. The project staff is also investigating electronic techniques for surveillance of traffic behavior and the detection of stalled vehicles.

The system consists of traffic detectors on the ramps and on the expressway at selected locations along the study section. Also in use are analog computers, an interconnection network, map display, and various data recording devices, including a paper punched tape output.

Some of the initial traffic studies being
made from the punched tape output are as follows:
(a) Interrelationships between volume, occupancy, and speed.
(b) Comparison of measured speed and speed calculated from volume and occupancy.
(c) Comparison of measured occupancy and density calculated from volume and speed.
(d) Comparison of lane traffic characteristics.
(e) Comparison of traffic characteristics between mainline stations.
(f) Changes in traffic characteristics just prior to congestion.
(g) Combination of shoulder lane volume and ramp volume resulting in maximum flow and satisfactory operation.
(h) Measurement of the effect of congestion on traffic flow and travel time.

The detection system is providing a comprehensive library of measurements which permit microscopic and macroscopic investigations, both qualitative and quantitative. The data logging subsystem is recording the measurements in a manner permitting full utilization of data processing equipment with a minimum of time and without loss of accuracy.

This extensive experimentation, like that at Detroit and New York, is providing a major testing ground for the application of traffic theories.

### 5.8 APPLYING TRAFFIC THEORY TO INTERSECTION CONTROL

The limited applications of road traffic theory have in general aimed at the same goal: to increase the proportion of time that traffic passing over a critical roadway is moving smoothly at mid-range speeds. The tunnel traffic flow control in New York accomplishes this aim by spacing traffic entering the tunnel so that vehicles will naturally move at mid-range speeds, at which flow is maximum.

Other experiments have been conducted to determine if traffic flow through a series of intersections can be increased by controlling the spacing of vehicles entering the critical area.

### 5.8.1 Dusseldorf's Signal Funnel

An application of this principle is reported from Dusseldorf (46) where, since 1954, traffic approaching certain intersections has been spaced. The "spacing" is accomplished by speed signals advising motorists to travel at 20,25 or 30 mph in order to reach an intersection at a time when the intersection signal will be green for their direction. This "signal funnel" as it is called by its developer, significantly increases the proportion of vehicles able to pass through an intersection without stopping. It is reported that this has the effect of increasing capacity by approximately 20 percent.

The signal funnel requires spacing the speed signals in advance of an intersection by an amount which varies according to the permissible difference in minimum and maximum speeds and the duration of green time. In many United States urban areas, it is doubtful that sufficient length of roadway is available in advance of critical intersections to effectively assemble vehicles in a moving platoon. This system also would not be as effective when traffic densities are so high that motorists are not able to drive at the higher speeds. However, the Dusseldorf experience does appear to merit serious consideration by United States traffic authorities for controlling boulevard traffic where grade intersections are spaced at intervals of $1,000 \mathrm{ft}$ or more.

### 5.8.2 Experiments with Pacer System in Detroit

A major application of the signal funnel is being tested on Mound Road in Warren, Mich., by the General Motors Research Laboratories in collaboration with county and state officials. This test has involved development of variable speed signs and installation of pre-signals. The experiment consists of measuring such parameters as transit time through the test section, number of vehicles stopped at intersections, and frequency of stops through the test section under three types of traffic signal opera-tion-non-interconnected, progressive, and pacer. Results reported to date by Morrison (33) indicate reductions in the number of stops required by motorists traversing the test section. The experiment is being continued, and a final evaluation has yet to be made.

### 5.8.3 Traffic Signal Control Experiments in Toronto

The first application of a general purpose computer to the control of a network of urban traffic signals has been reported from Toronto (19). Although the main findings of these experiments reported to date do not relate directly to road traffic theory, the use of a general purpose computer made it possible to study the detection of impending traffic congestion. It was also possible to consider new traffic signal operating strategies aimed at increasing the time during which fluid traffic conditions are maintained. Inasmuch as this work has not been reported in detail, the theoretical aspects of the work have yet to be evaluated.

However, the Toronto use of the general purpose computer has illustrated the challenges and opportunities facing traffic engineers and roadway operators. The ability of general purpose computers to handle large amounts of data at unbelievably rapid speeds indicates that the essential instrumentation is now available to apply more sensitive and detailed road traffic theories for improved traffic operations. The computer also is a powerful tool in evaluating traffic control experiments and, together with the interests of physicists and mathematicians in the theoretical aspects of road traffic flow, suggests that major improvements in traffic operations can be obtained.

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