INSTRUMENTATION DEVELOPMENT AND CONTRIBUTIONS FROM TRAFFIC FLOW THEORY

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•DURING the past 50 years, freeway operations has not generally been a major subject. In the mid-1960's when Cameron and Davis organized their excellent review of roads and highways for the Encyclopedia Britannica, the subject of operations was the last entry. In fact, it was just part of an entry called "Maintenance and Operations." One of the first entries in that article concerned the Roman roads, and that recalled an experience that I had while in Italy in 1968.

The Italian autostradas are among the outstanding highway construction accomplishments in the world today. In some cases the mileage consists more of tunnels and viaducts than of sections at grade. The autostradas generally incorporate the highest geometric design standards and safety features. It was the end of a 4-day national holiday when I saw them for the first time, and this magnificent system was littered for miles with accidents and congestion. This, of course, happens at times on the freeway systems in every country, but the contrast between the really beautiful road system and the level of traffic operations that night was especially sharp.

There seem to me to be 2 broad developments responsible for moving the status of freeway operations from an adjunct to maintenance to a major subject in its own right. One is the increasing dependence on freeways for travel, especially in urban areas. The other is the growth in knowledge and systems for improving freeway operations. This has taken place mainly in the past 15 years. Both of these broad developments seem likely to continue and to reinforce each other.

Freeway operations in the sense that I am using the term means applying intelligence to the minute-by-minute use of highways and giving the greatest possible service from the highways to the people who need to use them or are otherwise affected by them. The ability to apply intelligence depends directly on knowledge about the process to be controlled and on instruments available for sensing and controlling the process.

The sequence in which this ability is usually developed starts with some ideas or theories. Then a body of knowledge develops through the conduct of experiments using scientific instruments to measure and relate causes and effects. Based on this insight, larger systems of operating equipment are installed. These are justified by the predictions based on the small-scale experiments of benefits likely to be obtained. More knowledge then is gained from these larger installations and applied elsewhere. This is the stage we seem to be in now.

However, many of the accomplishments in freeway operations rest on traffic flow theory. The rapid development of instrumentation in the past decade has by itself enabled the implementation of many relatively straightforward ideas for improving traffic operations on freeways. For example, the ability to sense when traffic on the freeway is approaching capacity while there is still underutilized capacity on an adjacent service road enables the diverting of excess traffic to the frontage road. This provides a great improvement in operations in some cases and, of course, is just plain common sense.

The role of traffic flow theory in improving freeway operations is not so obvious as the role of a closed-circuit television system, for example. Traffic flow theory, however, has made some important contributions, and I believe it will be increasingly important in the future.

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The starting point in traffic flow theory was to determine the relationships among traffic flows, speeds, and densities. Studies of these relationships have led to what I believe is the basic contribution made by flow theory to operations. That is, to define quite sharply the concept and characteristics of an optimum traffic operating condition. This occurs at a density somewhat less than 75 vehicles per mile. Peak traffic often does not flow naturally in this optimum range but instead tends to become congested with densities of about 150 vehicles per mile. One of the main purposes of freeway surveillance and control systems is to increase the proportion of peak time when traffic operates in this more free-flowing fashion.

The concept of an optimum range for traffic flow is certainly not original with the present generation of traffic researchers and operators. In 1946 a paper on this subject by Joseph Barnett was published in the ASCE Proceedings. About the same time the concept was referred to by O. K. Normann in the first edition of the Highway Capacity Manual. It is implicit in Bruce Greenshields' early hypothesis that speed and density have a linear relationship, which gives a maximum flow at one-half jam density.

The contribution of traffic flow theorists has rather been to define more explicitly the form of the relationships among the several variables of traffic flow. They have done this by analogy with other physical processes, by mathematical analysis, and by more precise and exhaustive experimentation than was feasible in the late 1940's and mid-1950's.

Dealing with traffic as a mass process having characteristics of speed, flow, and density leads naturally to comparisons of traffic behavior with the flow of fluids. One of the broad fields of activity in traffic research relevant to freeway operations has been the exploration of this analogy. To the extent that traffic behaves as a fluid, the relatively complete understanding that is available in the published literature on fluid-flow characteristics can be applied to understanding traffic behavior as well.

The classic paper in this field was published in 1955 by two English mathematicians, Lighthill and Whitham, and was titled "On Kinematic Waves II. A Theory of Traffic Flow on Long Crowded Roads." They had written previously on the behavior of kinematic waves in hydrodynamics and had used this to deduce a theory "of the propagation of changes in traffic distribution along... roads." They state, "The fundamental hypothesis of the theory is that at any point of the road the flow (vehicles per hour) is a function of the concentration (vehicles per mile).... The hypothesis implies... that slight changes in flow are propagated back through the stream of vehicles along 'kinematic waves,' whose velocity relative to the road is the slope of the graph of flow against concentration."

The shape of this curve tracing the relationship between flow and concentration (or density) is therefore of fundamental importance. It establishes not only the flow that will occur at any given density of traffic on a given road but also the wave speed. Lighthill and Whitham do not specify a particular form for the curve, other than that flow is zero when density is zero or when there are so many cars jammed on the road that none of them can move. Between these 2 intercepts of the zero flow line, at some density that Lighthill and Whitham called optimum, flow would be maximum.

To suggest a formula for this curve, Harold Greenberg assumed the flow of traffic was similar to the flow of a fluid in one dimension. This led to a relationship, shown in Figure 1, which was continuous and defined over the entire range of density from zero to jam. It appeared to fit the data available at that time at least as well as any other continuous formula. Some called this the Greenberg Law, and it led to a certain amount of dispute. The dispute illustrates the strengths and also the weaknesses of applying physical analogies to understanding traffic behavior, and it is worth reviewing briefly here.

When he saw Greenberg's work, Whitham protested that there was no intrinsic justification for the assumption that vehicles would behave in the same way that fluids flowing in one dimension behave. The gist of the reply was that there was no intrinsic reason not to make the assumption, that the resulting curve fit the available data at least as well as any other continuous model, and that making the assumption had some useful benefits.

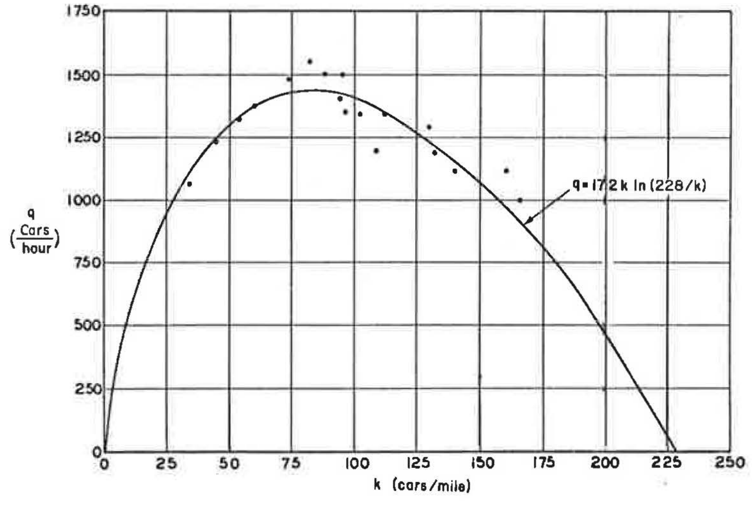

Figure 1. Flow, q cars/hour, versus density, k cars/mile.

Soon after this dispute we were able to obtain a larger and more precise sample of flow-density data. Based on this Leslie Edie published a paper proposing 2 separate equations for the curve (Fig. 2). One would apply at densities less than optimum and one at higher densities. The main point is that the data showed that the relationship between flow and density was probably not continuous in the region of maximum flow. The 2 curves Edie proposed did not meet: The one for low densities went to a higher value of flow.

This discontinuity in the flow-density relationship is a most important point to appreciate. It became evident only with a large sample of data, the processing of which

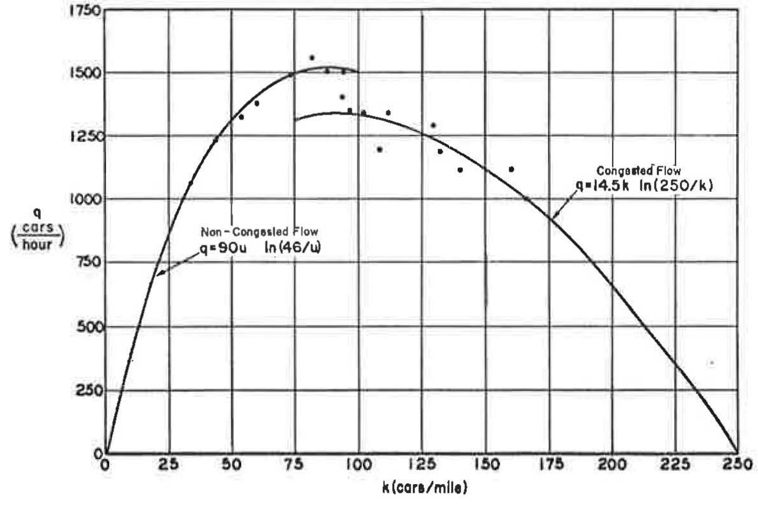

Figure 2. Flow, q miles/hour, versus density, k cars/mile, for congested and noncongested flow.

had previously not been feasible because there was not suitable instrumentation. With the development of an electronic traffic data acquisition system, that bottleneck was broken. The discontinuity indicates that there are limits in the application of hydrodynamics to describe traffic.

A particle of fluid accelerates or decelerates at rates that are determined by factors external to the particle. Whether an acceleration or a deceleration is called for makes no difference to the particle. In traffic, however, a vehicle and its driver have different mechanisms for accelerating and for decelerating. The perceptions and risks are altogether different in the 2 cases. Forbes showed experimentally in the late 1950's that drivers react more slowly to an opportunity for acceleration than to the need for a deceleration. This asymmetry appears to be related to the observed discontinuity in traffic behavior at optimum density.

There have been both strengths and weaknesses in the use of the hydrodynamic analogy to understanding traffic behavior. This analogy has produced valuable insights into the wavelike propagation of disturbances along a traffic stream. Carrying the fluid-flow analogy too far, however, tended to mask the discontinuity at peak flow, which is one of the most significant characteristics of road traffic behavior.

It is significant because it can explain why shock waves develop at a bottleneck and why flow through a bottleneck is lower when traffic is congested than when it is free-flowing. Harold Greenberg and another researcher at the Port Authority were first to demonstrate experimentally that more traffic would flow through a roadway if it were kept free-flowing than if it were allowed to become congested. One of the major purposes of the instrumentation we have developed since then has been to keep traffic densities below 75 vehicles per mile. Figure 3 shows the contribution this makes.

Figure 3 shows the end result of a cooperative study by staff at the Port Authority and at IBM in which a computer was applied to control tunnel traffic densities. When the controlled flow in April is compared with the uncontrolled flow in October, a major improvement is clear. To determine whether this was possibly due to seasonal effects, we compared flow in other tunnels for the same 2 periods (Fig. 4). If anything, flow in April is lower than flow in October.

Another area where traffic theories have made a contribution is in clarifying the measurement of traffic density, or vehicles per mile. This can be measured by counting traffic flow and dividing by average speed: Vehicles per hour divided by miles per

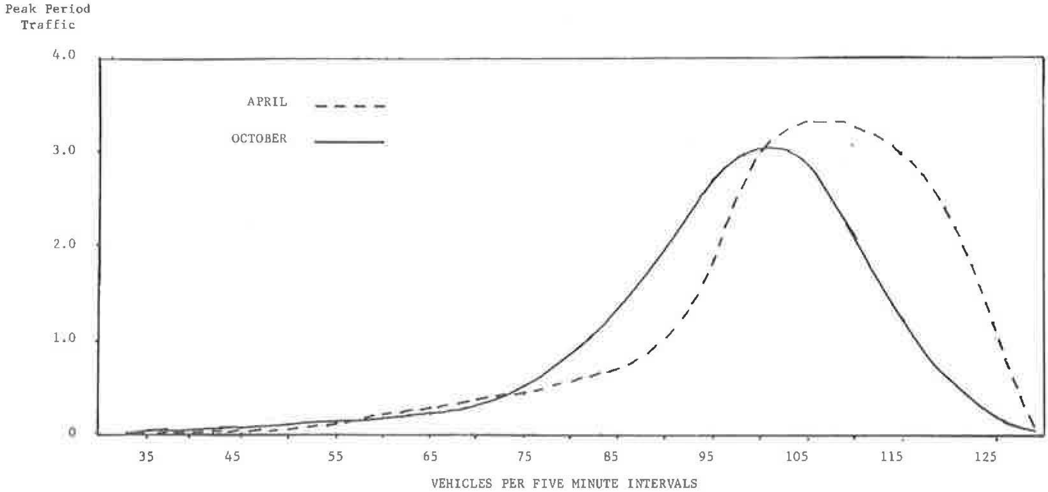

Figure 3. Controlled traffic flow in April versus uncontrolled traffic flow in October in the near lane of the Lincoln Tunnel south tube during p.m. peak.

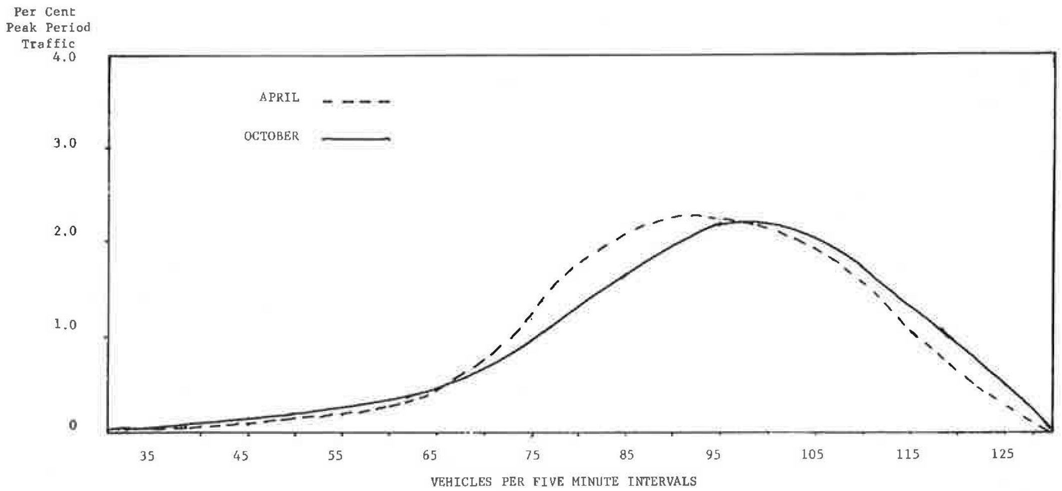

Figure 4. Uncontrolled traffic flow in April versus uncontrolled traffic flow in October in the north and center tubes of the Lincoln Tunnel during a.m. and p.m. peaks.

hour equals vehicles per mile. If both the flow and the average speed are determined at a point, there is no physical reality to the number derived by this calculation. This is a confusion that seems to be embedded in traffic analysis. It arises because of the 2 ways in which speeds can be averaged.

As Wardrop pointed out at the Road Research Laboratory in the early 1950's, the speeds of vehicles can be measured for some time interval as successive vehicles pass a point and then averaged. He called this time-mean speed. Or the speeds of vehicles present on a length of roadway at an instant can be measured and averaged; he called this space-mean speed. The dimensions for density are valid only when space-mean speed is used. This, of course, is far more difficult to measure than time-mean speed, but that does not alter the fact that densities derived solely from measurements at a point have no physical meaning. This distinction is important in freeway operations because density is an important predictor of flow.

These two illustrations of the contributions of traffic flow theory are drawn from just one branch of the science and only begin to suggest the scope of theory that has been defined. Valuable work has been done in studies of car-following behavior. Herman, Rothery, Potts, Gazis, and others have provided many insights, for example, into the stability and instability of traffic streams, the role of acceleration noise, and the relationship between these microscopic views of traffic behavior and the mass flow studies just described. Statistical aspects of traffic have been explored by many researchers such as Buckley in Australia and Jewell and Haight in the United States. Queuing theory has many applications in describing traffic operations. Computer simulation has been applied to the study of traffic flow by a great number of researchers. Both psychological and simulation studies of driver behavior have been made, and the work by Senders is especially noteworthy. Nearly all of this has happened in just the past 15 years, and in that time there has been created an extensive literature that constitutes a science of traffic flow.

Much of this work has been accomplished because mathematicians and physicists became interested in contributing insights from their basic disciplines to the understanding of road traffic behavior. This has resulted necessarily in contributions scaled to the resources available to the individual researchers and to their interests rather than to the needs of a coordinated effort to understand traffic behavior. The result has been to advance some aspects of traffic flow theory faster than others.

Chief among the important questions that still need answers is this: What determines the capacity of a freeway link? I believe an important part of the answer will be the description of how drivers process information. There seems now to be increasing interest in this question and also increasingly sophisticated instruments available for the researchers. Probably more than the other branches of traffic flow theory, however, this work did and still does require the development of instruments that force the state of the art. Instrumentation development has generally played an important part in the development of traffic flow theory, but this matter of driver information processing is especially dependent on it.

Full-scale experiments to measure driver reaction times in a range of roadside environments were reported by Forbes and others in the late 1950's. These used split-frame photography to show the roadside environment, the positions of the several cars to which the experimental driver was reacting, and the position of the controls on the experimental vehicle. Although the films were difficult to read, these experiments did capture the major variables. Since then considerable strides have been made in measuring the 3 principal elements here: the roadway, the vehicle, and the driver. Simulators have been developed by using both movies of actual roadside environments and TV camera views of model terrains. Vehicles have been highly instrumented and, in the case of the simulators, controlled movements are generated by computers to provide varying types of road feel to experimental drivers. The drivers are sensed for galvanic skin response, heartbeats, breathing, and in some cases brain waves. Several attempts have been made to measure driver eye movements.

There is still a long way to go in this effort, and the contribution this research will make to freeway operations is just beginning. For example, one of the most important elements in research on driver information processing is to determine where the driver's attention is being directed as he moves his vehicle through the road environment. The instrumentation to measure driver eye movements is still relatively cumbersome, and its presence may well influence experimental results. The brain-wave instrumentation is particularly liable to this form of error. There is a more serious difficulty in that, even with excellent measures of eye movement, brain waves, heartbeats, galvanic skin response, and breathing, psychologists are not agreed on the interpretation of the data. When the experiments are conducted in real driving situations rather than in simulators, there is a lack of instrumentation for sensing accurately the distance between the experimental vehicles and objects along the road, such as abutments and other vehicles. Furthermore, there is need for more research to quantify the information content of the actual environment.

These few examples suggest how much remains to be done in developing the basic scientific knowledge needed for freeway operations as well as for freeway design. This is certainly a worthy challenge for the kind of technological expertise that was marshalled so successfully for America's space program.

Although much remains to be done in developing instrumentation and knowledge concerning driver information processing, much has already been done in applying instrumentation to improve freeway operations. Historically a major focus of this effort has been to extend the limited-access feature, which is the prime characteristic of freeway design, by metering the flow of traffic onto the freeway when necessary to prevent congestion on the freeway itself. This work was initially based in part on the Port Authority experiments that I described earlier, but it rapidly developed independently of the tunnel work. Today, in fact, the kind of improvements we have obtained by keeping tunnel traffic moving plays little if any part in the benefits being obtained on the freeways. I believe there are places where the same type of operation being developed for the tunnels can also benefit freeways, but this will require more intensive surveillance and control systems than have been applied to date on the freeways.

The freeway benefits have instead come more from diverting excess traffic to other roads that are in the corridor served by the freeway and have capacity available. The access-control systems are also valuable in allocating priority movement to buses. In places where bus movements are heavy, this can be an output from the control systems and has an extremely high payoff in moving more people on the freeways with less delay.

Another major focus of the effort to improve freeway operations has been to sharpen the detection, handling, and removal of disabled vehicles and other incidents that reduce capacity. Such incidents occur every day and often cause a wide variation in the time required for trips. Now there is increasing attention being given to instrumentation that can inform motorists about these events and help them to find the best alternate routes.

The development of instrumentation for these purposes has occurred in about the same time frame as the development of traffic flow theory. In 1959 tunnel traffic flow control began on a pilot basis. The first major installation of surveillance equipment was on the John Lodge Freeway in Detroit in 1960 when 14 closed-circuit television cameras were installed to observe a 3.2-mile section. Shortly after, in 1962, ramp-metering operations began with a pilot system in Chicago. In 1964 ramp-metering experiments started in Houston as well. A few ramp closures were tried in Los Angeles, and then in 1966 ramp metering started there too. A few other cities have also conducted experiments and made plans for freeway surveillance and control systems, but these have been the major actors. I believe the development of such systems in Europe and Japan has been more recent.

The pace of instrumentation development during this time has been fast. For example the automatic stoppage detection system that we are using now at the Lincoln Tunnel is actually in its fourth generation. We started with an array of electromechanical timers in the late 1950's. Next was a vacuum tube electronic curcuit in the early 1960's. Then in 1965 we installed a system using solid-state devices but still wired in a special purpose circuit. Now, of course, we use computers and have far greater flexibility and logical power. This advance in logic has been paralleled by advances in reliability and economy. Similar advances have occurred in vehicle detection and in signal transmission. There are still weaknesses in the instrumentation available for surveillance and control, but these trends toward better performance at lower cost are likely to continue.

There will be new forms of instrumentation available soon. I believe the next major development in instrumentation for freeway operations will be in automatic vehicle identification. Although the electronic license plate for all vehicles may not be around the corner, the technology is available now for full-scale testing, and the potential benefits are important in many applications. Apart from traffic control, the wide application of automatic vehicle identification can assist motor vehicle administration, law enforcement, maintenance, planning, financing, and fleet operations. The initial application for bus identification is being made now at the Golden Gate Bridge, and we expect to have one in New York in the very near future.

A major theme in the development of instrumentation for these systems has been the role of television versus digital systems. In pioneering this broad field of traffic surveillance, Detroit researchers set a pattern that was generally not copied in other areas. Television has been a major element in city street traffic surveillance systems developed elsewhere during the 1960's, chiefly in Europe and Australia. For expressway surveillance, however, Chicago went the all-digital route in 1962. Even today the Chicago expressway surveillance system makes hardly any use of television. The pattern in Houston and in the tunnel surveillance and control systems has been to use both television and digital systems. Television is a valuable adjunct to a digital system for research and also for helping in the policing of roadway operations. I believe that over the long run it will gradually be phased out in favor of fully automated digital control systems. This, in fact, did happen in Detroit.

Inherent to some extent in this dichotomy between television and digital systems has been the role of police and engineers. Where surveillance is a supplement to existing police traffic operating groups, television has been especially useful. However, increasing demands on police for other functions and their increasing salary costs increase the stress on fully automatic systems.

It seems clear that the main burden of development in this field of freeway operations will continue to be carried by engineers relying on automatic equipment. We have a way to go yet before freeway operations can make much use of automatic control theory that includes prediction and feedback, but I believe that is where we are heading. On line, real-time systems will predict traffic demands and will target service levels for those demands; they will sense conditions that affect the service being given for that demand; they will alert police wreckers, ambulances, and debris-removal equipment; they will estimate the probable consequences of alternate control strategies and select the optimum; they will drive entrance ramp controls, diversion signs, and reversible lane devices such as lane signals and delineators; they will measure the traffic demands, densities, and delays actually on the system and analyze their own performance; they will call automatically for maintenance on defective system components; and they will learn from their experience. This is the challenge we have, and the ability to meet it is here.