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Vehicular Traffic Flow

The interaction of driver-car units on roads is now being studied by physical and mathematical methods. The results have already been used in the solution of traffic problems

by Robert Herman and Keith Gardels

Science traditionally advances by the interaction of observation, theory and experiment, and the success of the scientific method has often recommended its application to problems of daily life. One such problem is the flow of automobile traffic. This problem has not lacked practical students: traffic engineers have obviously made important contributions to its solution. In recent years, however, it has become apparent that the flow of traffic lends itself to a more general kind of physical and mathematical analysis. The objective of this theoretical approach is to offer some insights that will give the practitioner something more than rules of thumb and graphs of vehicular flow for improving traffic systems.

Traffic theory, tested by experiment, has recently brought about a significant improvement in the large daily flow of vehicles between the state of New Jersey and the island of Manhattan. The achievement must be regarded as limited: virtually all the flow is carried by three arteries—the Holland Tunnel, the Lincoln Tunnel and the George Washington Bridge—and vehicles channeled through any such structure are conspicuously subject to analysis and control. Nonetheless, there is reason to believe that traffic theory can be applied successfully to more commonplace situations. It may be of fundamental value in helping to define the forces that act on a driver and to understand his responses to them. It may help to alleviate some of the problems that arise on crowded city streets and on multilane highways.

We wish to emphasize, however, that traffic theory in its present state of development has come about as far as astronomy had before Kepler. Much remains to be done, not only in acquiring and analyzing data but also in persuading theoreticians to correlate their thinking with reality and traffic engineers to accept the contributions that theory can make to their problems.

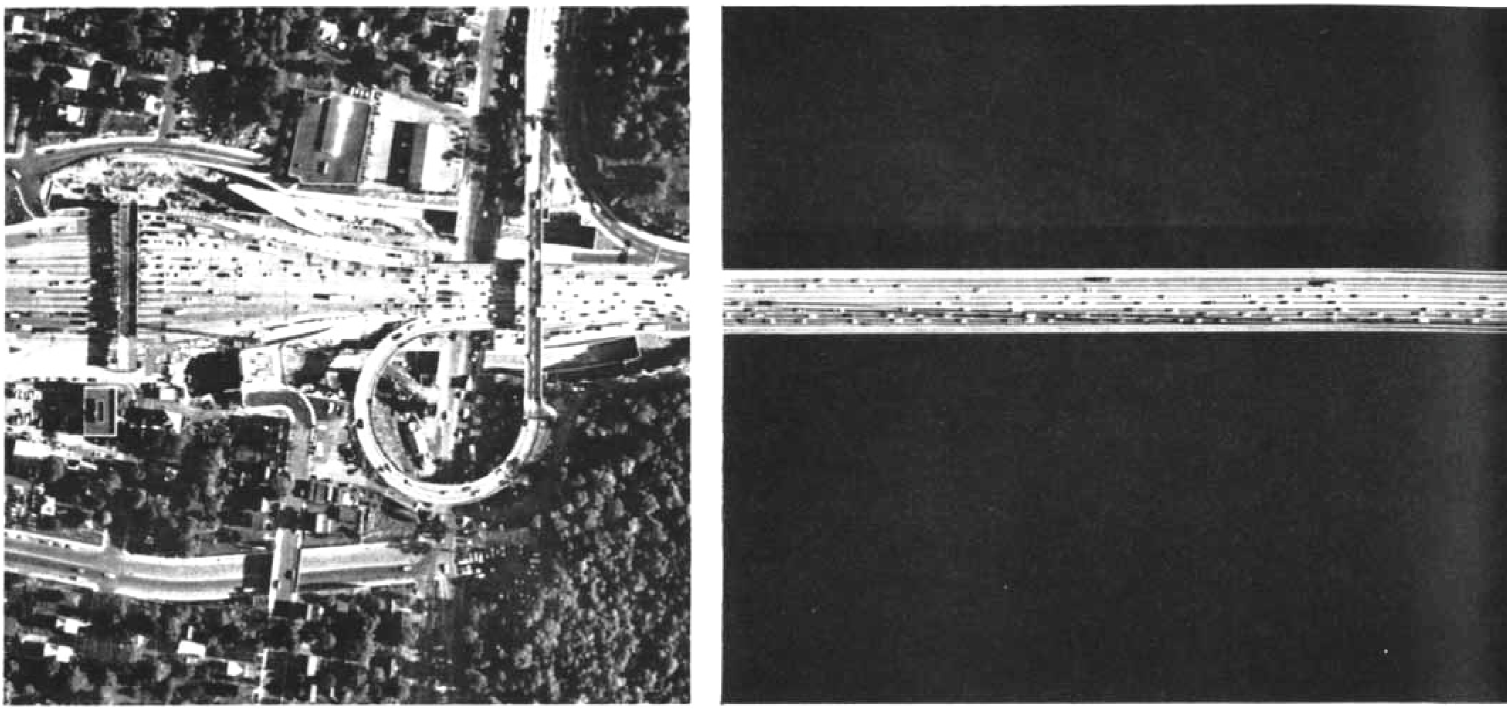
A theoretician is likely to take one of two conceptual approaches to traffic flow. One concept views the vehicular stream as either a compressible fluid (a single automobile is regarded as part of the fluid and is not considered individually) or the collection of molecules in a gas (the individual cars are regarded as discrete but are treated in a purely statistical manner). The second concept focuses primarily on describing traffic flow on the basis of the behavior of the individual driver-car unit.

The first approach, with its macroscopic over-all viewpoint, has some appealing features. A traffic stream on a single-lane, no-passing stretch of road does indeed approximate a fluid whose rate of flow depends primarily on its density. Up to a point the rate of flow increases as the concentration of vehicles rises; thereafter the rate of flow decreases if the density continues to increase. Similarly, the analogy of traffic flow to the motion of molecules in a gas—an analogy in which automobiles are assumed to be isolated most of the time and interacting with each other only at intervals—has some application in reality.

One might well ask, however, if the resemblance of traffic to a fluid or molecules in a gas is only superficial. There seems to be little justification for assuming that the actual behavior of traffic is controlled by the same forces associated with liquid or molecular dynamics. Drivers, unlike molecules, make individual decisions.

The appropriateness of the first approach can be better judged by looking at the second concept dealing with the fundamental unit of traffic: the driver and his car. The behavior of the driver-vehicle unit has been extensively studied by a group of theoreticians and has developed into what we have called follow-the-leader theory. Among those who have worked most intensively on this approach are Elliott W. Montroll of the Institute for Defense Analysis, Renfrey B. Potts of the University of Adelaide, Denos C. Gazis of the International Business Machines Corporation and Richard W. Rothery and one of us (Herman) at the General Motors Research Laboratories.

We base follow-the-leader theory on an observable phenomenon that occurs whenever a driver draws fairly close to the vehicle ahead of him. The phenomenon is that within a region of about 200 feet he begins to interact with the leading driver. The distance is somewhat less



DENSE AND COMPLEX TRAFFIC FLOW characteristic of metropolitan areas appears in these aerial photographs by the Port of New York Authority showing the approaches to the George Washington Bridge and portions of the span at a peak period on a week-

if the follower has plenty of room to pass; on the Edsel Ford Expressway in Detroit, where there are three lanes each way with passing allowed, the region of interaction is about 175 feet. The distance is somewhat greater in a no-passing situation, such as that presented by the Holland Tunnel; there vehicles begin to interact within about 250 feet.

Follow-the-leader theory attempts to describe the behavior of a single lane of fairly dense traffic in terms of the detailed manner in which vehicles follow one another in the traffic stream. This condition of one-lane traffic with no passing is more common than the motorist accustomed to multilane turnpikes might think. No-passing situations still exist, in law or in actuality, on many stretches of two-way roads and streets, in tunnels and on bridges. Even on multilane highways dense traffic often forces a driver to stay in one lane.

The basic idea expressed in follow-the-leader theory is that a motorist driving along a highway behind another vehicle attempts to follow that vehicle in a stable manner. Therefore we assume that the motion of his car obeys what we might call a car-following law, which can be formally described by some mathematical relation.

Such an expression must take account of the fact that the behavior of the following driver-car unit is a result of some psychological phenomenon. With that in mind we have reduced the description of the behavior of the driver-car unit to an equation that says the driver's response, after a time lag, is a product of the measurable environmental stimuli and a factor we call the driver's sensitivity coefficient. Put another way, the equation says: A driver faced with a situation (the stimulus) does something about it (the response). How much he does represents his sensitivity coefficient. How quickly he does it determines the response lag of the man-machine system.

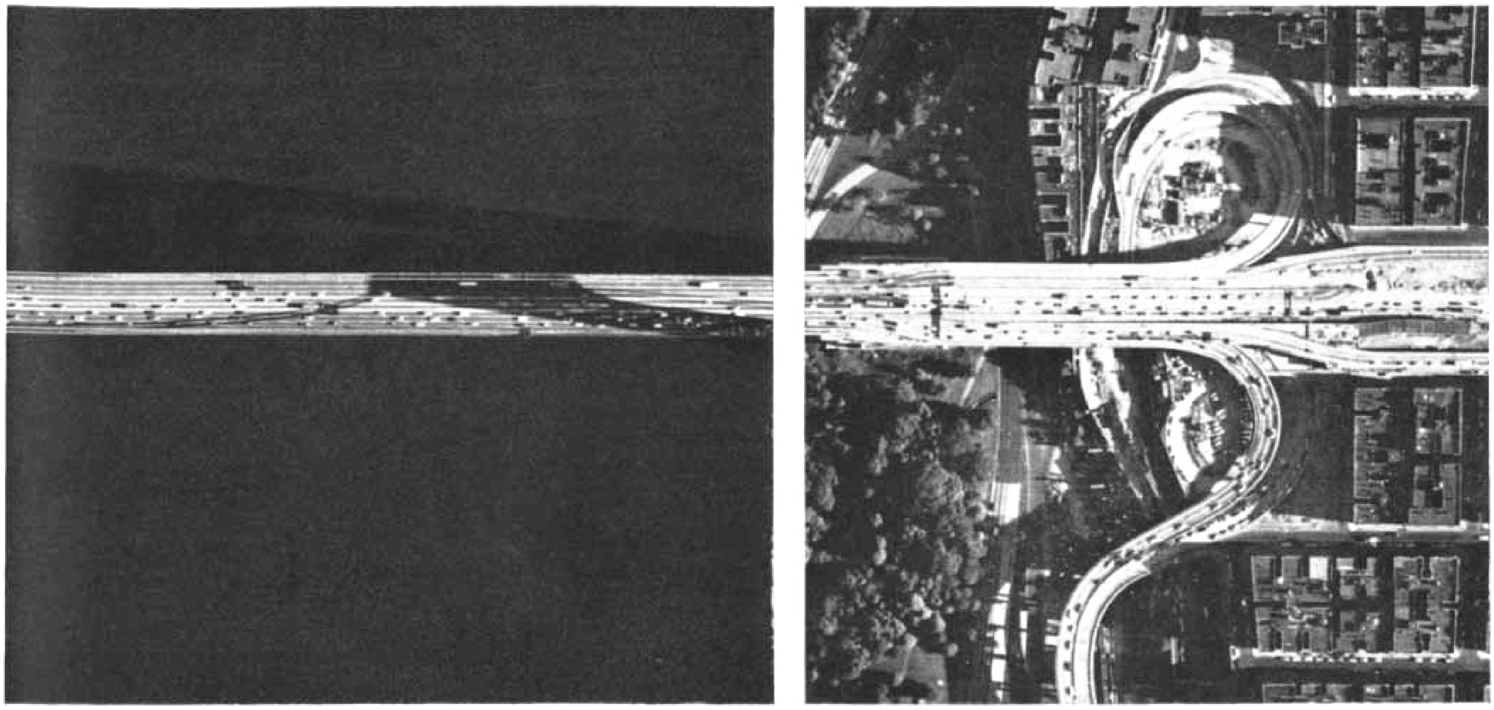
Necessarily such a car-following law is a grossly simplified description of a very complicated response to the world of stimuli that confronts a driver. The phenomenological approach taken in this theory lumps together a large number of mechanical and human characteristics that can be handled individually only with great difficulty. A complete stimulus-response description would have to distinguish, for instance, between a teenage driver with his arm around his female companion and a husband with his wife commenting from a somewhat greater distance. Nevertheless, we have been able to determine through a number of controlled experiments that the law represents a reasonable approximation of reality.

One might expect that if we were to attempt to supply the exact form of our equation, we would have to build a complicated mathematical structure in order to express something like the real traffic situation. Actually we have found through experiment that the ingredients of the equation—the response, the stimulus and the sensitivity coefficient—can be set out in relatively simple form. We shall discuss these ingredients one by one and at the same time describe the experiments by which we arrived at them.

The response is determined by a driver through his accelerator and brake. They provide his only practical means of responding to changing stimuli in a one-lane, no-passing situation. The equation describes the response as the acceleration or deceleration of the trailing car after a time lag. Acceleration, deceleration and time lag are easily and directly measurable quantities. The total time lag of both driver and vehicle is derived through a mathematical comparison of the response with the stimulus under study.

The main stimulus to which a driver responds might logically be expected to be the distance between him and the car ahead. Our experiments showed, however, that the dominant stimulus is instead the relative speed of the two cars. In other words, a following driver attempts to keep at a minimum the difference in speed between his car and the leading car.

We found this rather surprising stimulus-response behavior in follow-the-lead-



day morning. Almost all traffic between New Jersey (*left*) and Manhattan (*right*) is carried by this bridge or by the Holland or Lincoln tunnels. In heavy traffic all of the patterns are similar, but at the bridge it is possible to observe the entire flow at one time.

er experiments conducted on a test track at the General Motors Technical Center in Warren, Mich. We connected two cars with fine piano wire so mounted that a slipping friction clutch would keep it taut no matter what the two cars were doing [*see top illustration on next page*]. Mounted with the clutch were instruments that recorded such information as car spacing, speed and acceleration; originally that information was registered on an oscillograph but now it is recorded on magnetic tape and processed by means of an electronic computer. After the equipment was in place we said to several drivers in succession: "Follow the lead car in what you consider to be a safe manner." The various drivers of the lead car randomly varied their speeds from 10 to 80 miles per hour and included some drastic braking actions. Invariably in these tests it was clear that the governing stimulus for the following driver was relative speed rather than distance.

Between two interacting cars the distance will therefore vary, sometimes because of the nature of car-following behavior, which is accentuated by the time lag in the response of the follower, and sometimes because the follower decides that his speed should be somewhat greater or less than the leader's for some reason. Our laboratory has tried experiments in which the follower was asked to keep a constant distance, aided by spacing information on a dial in his car. It was found that in order to keep the pointer steady at, say, 100 feet as the speed of the leading car varied he had to accelerate and brake with distinct unevenness.

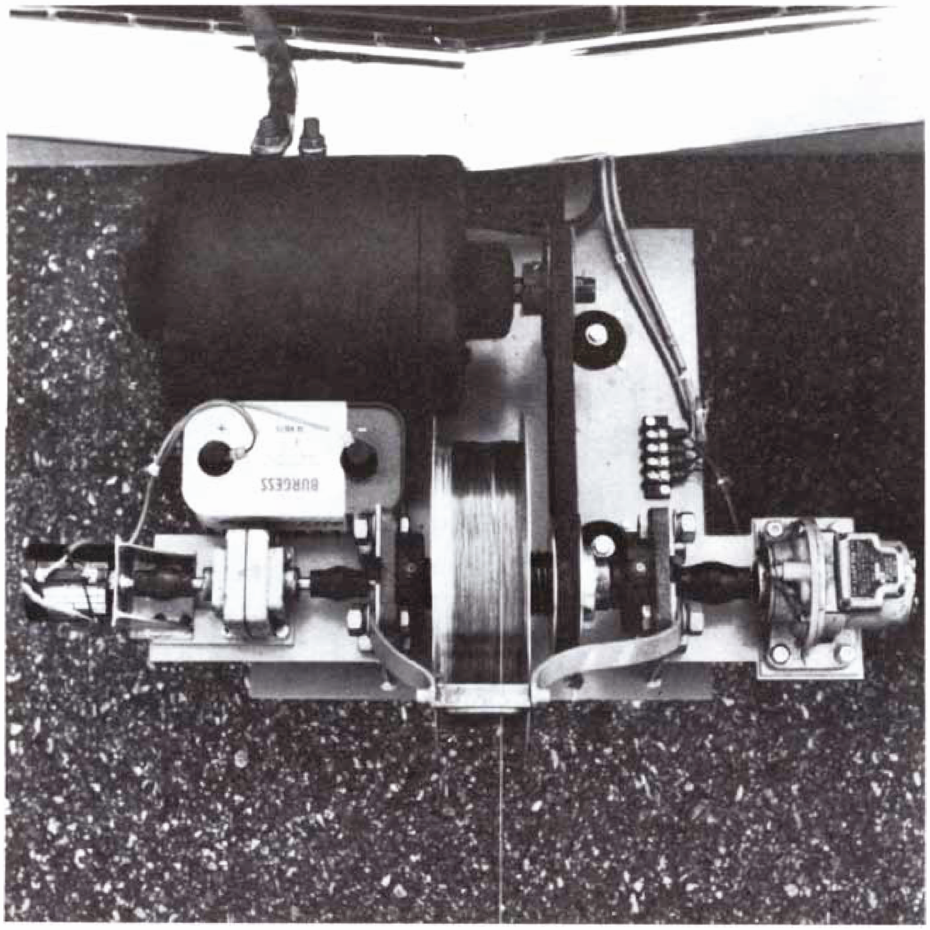
The final factor in the equation, the sensitivity coefficient, we took at first, for mathematical convenience, to be a constant. Our initial experiments indicated that the resulting values for this coefficient did give an equation that approximated reality. Later, however, we conducted experiments under real traffic conditions and the controlled conditions of the test track to see if the sensitivity varied with changes in the spacing or speed of the vehicles. These experiments indicated that the driver's intensity of response per unit stimulus—his sensitivity coefficient—varied inversely with the spacing. As the distance between cars decreased, the sensitivity of the following driver's reaction seemed to increase.

In sum, the follow-the-leader equation works out to show that a driver tries to keep the relative speed between him and the vehicle in front as small as possible, and that the closer he is, the more attention he pays to the problem [*see illustration on page 39*]. If he is far away, he drives in a manner that is more or less independent of what the driver in front is doing.

Armed with these findings about the interaction of two drivers, we turned our attention to the question of the interactions of several drivers. Our idea was that insights about such interactions, which occur in a stream of vehicles, would provide a basis for understanding traffic flow and perhaps for improving it.

Theoretically a condition of maximum flow would exist if all the cars in a stream proceeded bumper to bumper at the highest speed allowed by the nature of the road. What actually happens is of course different because of driver interactions. The manner in which drivers interact in a stream leads to a flow-concentration relation that can be expressed mathematically and might be called an "equation of state" for traffic. The equation reflects the fact that between the extremes of zero flow because there are no cars in a lane and zero flow because of a traffic jam there is a maximum flow. That steady-state flow is the product of the concentration and average speed of the traffic. We call the average speed of a traffic stream at maximum flow the characteristic speed. It has a value reflecting the total traffic situation: driver, vehicle and road characteristics as well as the impact of traffic ordinances, weather and the time of day or week.

On the basis of these calculations we undertook some studies of actual traffic situations in three tunnels in the New York City area—the Holland, the Lincoln and the Queens Midtown—all char-



CAR-FOLLOWING EXPERIMENTS, designed to demonstrate how one driver follows another, used this equipment mounted on front of following car. A clutch kept taut the piano wire connecting the two cars; instruments recorded such data as spacing and relative speed.

$$\overbrace{\frac{d^2x_{n+1}(t+T)}{dt^2}}^{\text{ACCELERATION AT }(t+T)} = \frac{\overbrace{G}^{\text{SENSITIVITY COEFFICIENT}}}{s(t)}\overbrace{\left[\frac{dx_n(t)}{dt} - \frac{dx_{n+1}(t)}{dt}\right]}^{\text{RELATIVE SPEED AT TIME } t}$$

FOLLOW-THE-LEADER THEORY is expressed as an equation. It describes the manner in which one driver follows another in a stream of traffic. Symbol x is distance; t, time; T, a time lag; G, the following driver's gain constant; $s(t)$, spacing of the two vehicles at time t; n, the nth vehicle in a line of vehicles; $n + 1$, the vehicle behind the nth. The d's represent differentials. The equation expresses experimental findings that a driver responds predominantly to changes in relative speed between his vehicle and the vehicle ahead.

$$\frac{\partial f(v,t)}{\partial t} = -\overbrace{\frac{f\ \ f^0}{T}}^{\text{RELAXATION TERM}} + \overbrace{(1-P)c(\bar{v} -\ \ v)f}^{\text{COLLISION TERM}}\overbrace{\lambda(1-P)c\,[c\delta(v -\ \ \bar{v})f]}^{\text{ADJUSTMENT TERM}}$$

THEORY OF MULTILANE FLOW is similar in spirit to Boltzmann equation used in the kinetic theory of gases. The important difference is the incorporation of drivers' will into the traffic equation. Symbol f is the actual speed distribution; f^0, desired speed distribution; t, time; T, relaxation time; P, probability of passing another vehicle; c, traffic concentration; v, average speed of traffic; v, speed of an individual car; λ, a weighting function that depends on the concentration of the traffic; δ, the Dirac delta function. The symbols resembling backward 6's are known as mirror 6's and represent partial derivatives.

acterized by heavy traffic moving in single-lane, no-passing situations. The Holland and Lincoln tunnels are under the jurisdiction of the Port of New York Authority, and in our studies we had the close collaboration of Port Authority staff members, particularly Leslie C. Edie and Robert S. Foote.

First, follow-the-leader experiments were conducted in the tunnels, again using two instrumented cars connected with piano wire. In the Holland Tunnel, for example, 11 different drivers made runs between Manhattan and New Jersey at randomly chosen times of day, including evening rush hours. As before, we studied the correlation between stimulus and response, between the relative speed of the two cars and the acceleration or braking of the rear car, thereby determining the time lag and sensitivity coefficient of the trailing driver. These experiments, however, differed from those on the test track in that both of the cars moving through the tunnel were necessarily influenced by the conditions of the traffic stream.

After these experiments were conducted, our next concern was to obtain some measurements of typical traffic in the tunnels. We would thus have data on the different quantities to be found for such variables as flow, concentration and vehicle speeds. In one of the measurements two photocells were mounted 12.9 feet apart on the ceiling above the center of a lane in the Holland Tunnel. Instruments connected with the photocells recorded the passage of each vehicle. This experiment collected data over 10 days at various times and under a variety of conditions, yielding a sample of about 24,000 vehicles, enough to establish the main characteristics of the traffic stream. For example, the data indicated that the characteristic speed in the tunnel—the speed at which maximum flow occurred—was 19 miles per hour.

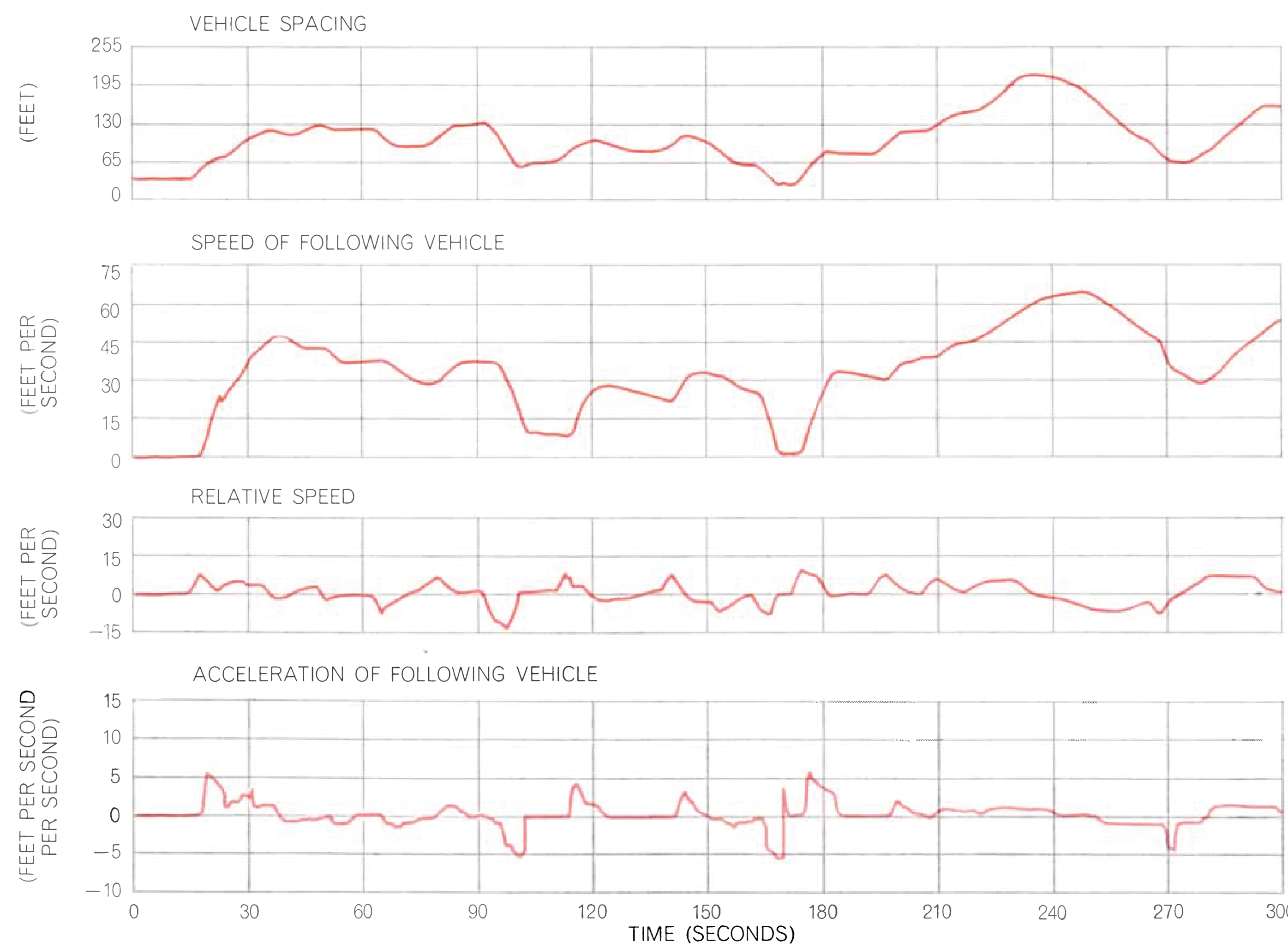
The results predicted by follow-the-leader theory closely approximated the characteristics derived from the traffic measurements in the tunnel. For example, the characteristic speed determined by the car-following experiments was 18.2 miles per hour. Plotted as curves, the data obtained from experiment showed a close fit with the results predicted by the car-following equation. Considering the complicated nature of actual traffic and the relative simplicity of follow-the-leader theory, we found it most gratifying to get results of the same order from observing two interacting vehicles as we had from looking at

24,000 in a given tunnel environment.

These tunnel studies have enabled us to understand something about the nature of the interactions of vehicles in a single lane of traffic. If the concentration of cars is low, a driver goes at what can be called his desired speed: the speed that seems most suitable to him in the circumstances. The flow through the lane will of course increase for a time as the number of vehicles in the stream increases. In other words, during this period there is an approximately linear relation between concentration and flow. Plotting the traffic through each of the three New York tunnels as a flow-concentration curve, we found that this linear relation was identical from tunnel to tunnel. Apparently a typical motorist drives through one tunnel in essentially the same way as he does through another up to a certain point of traffic concentration, no matter how the tunnel environments differ in such particulars as width, lighting and road profile.

When drivers have to interact with other cars, however, the situation changes markedly and with significant results for the flow. Motorists begin to react differently to the different tunnel environments. As a result the curves for the tunnels start to vary: they bend over at different rates and pass through different maximums for each tunnel. This maximum is lowest for the Holland Tunnel, the oldest of the three, and thus that tunnel's characteristic speed is also lowest. The Lincoln and Queens Midtown tunnels appear on the basis of somewhat less information to have characteristic speeds of 20 and 22 miles per hour respectively. As the traffic concentration increases sufficiently beyond the point of maximum flow in any tunnel, interactions cause disruptions in the flow and may even produce traffic stoppages. Stoppages occur in practice sooner than one might predict theoretically. As far as we know, no one has measured a moving traffic stream with a concentration of more than about 110 vehicles in a mile of lane.

Between maximum flow and standstill in a situation where the concentration of cars continues to rise, interactions produce disturbances best described as shock waves. A certain car in a lane slows down for some reason. So perforce does the next car, perhaps more abruptly because the driver reacts too slowly or too vigorously or both. In any case the disturbance is propagated back along the line for some distance [*see illustration on next page*]. The disruption may well reach a point at which one or more drivers have to stop, if only momentarily. Gradually the wave subsides as the first car and then the others regain their speed, but meanwhile some of the affected drivers may have had to perform extreme maneuvers of acceleration or braking. This is the accordion effect so familiar in crowded single-lane conditions. In a flow of high density it may occur repeatedly, considerably



TEST RESULTS are shown by graphs based on information printed by a computer during a follow-the-leader experiment in which the driver of the leading car varied speed randomly and the other driver followed in a manner that he thought safe. The cars were linked by piano wire as shown in top illustration on opposite page. A speed of 30 feet per second is approximately equivalent to 20 miles per hour; therefore in the period of five minutes shown here the speed of the leading car ranged from 0 to 40 miles per hour.

reducing the productivity of the lane.

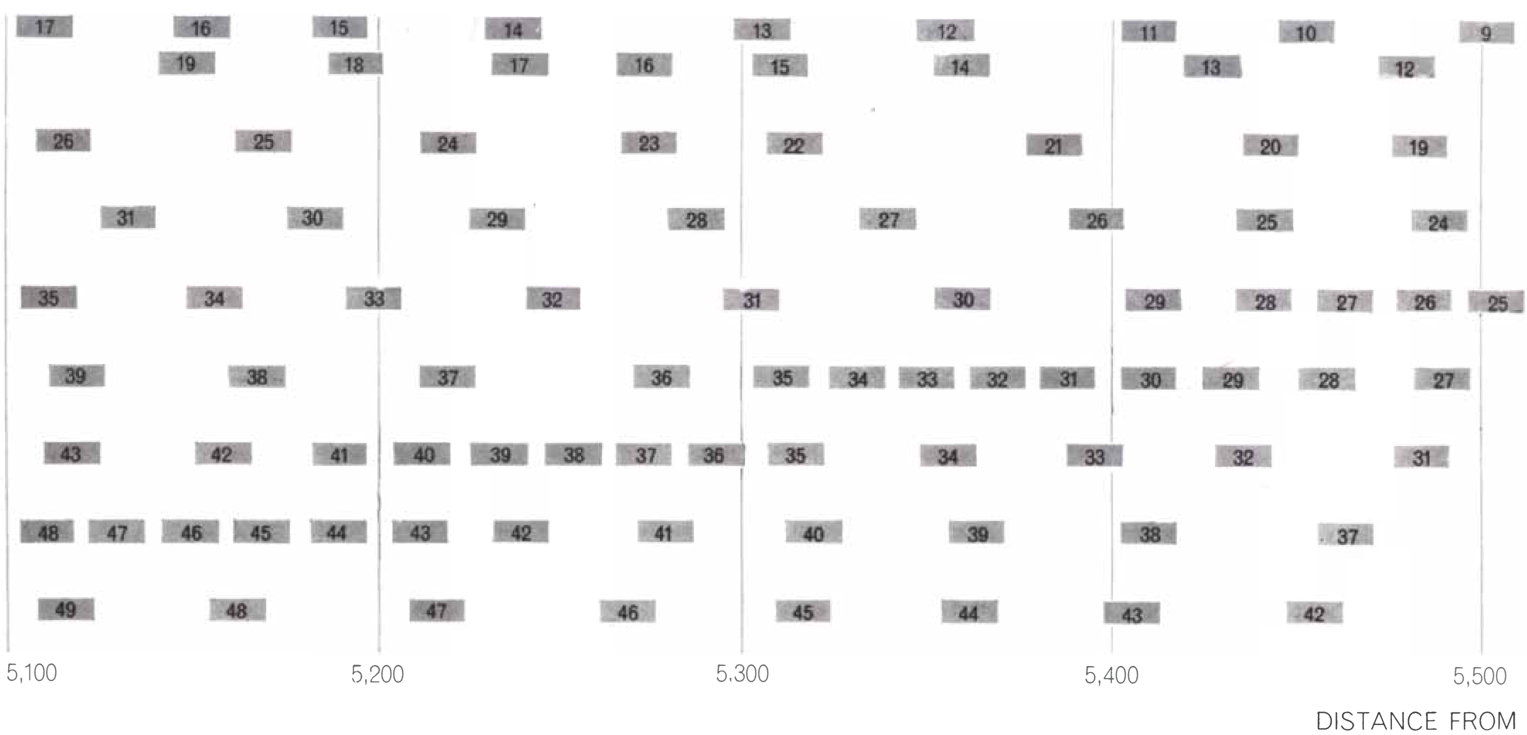
Often a shock wave is generated by some feature of the road, such as an upgrade. A motorist fails to realize he is on an upgrade or fails to accelerate in such a way as to maintain speed on the upgrade or has a car with poor acceleration. As a result he loses speed and a shock wave begins. In a crowded single-lane situation where passing is not possible such a feature becomes a chronic bottleneck.

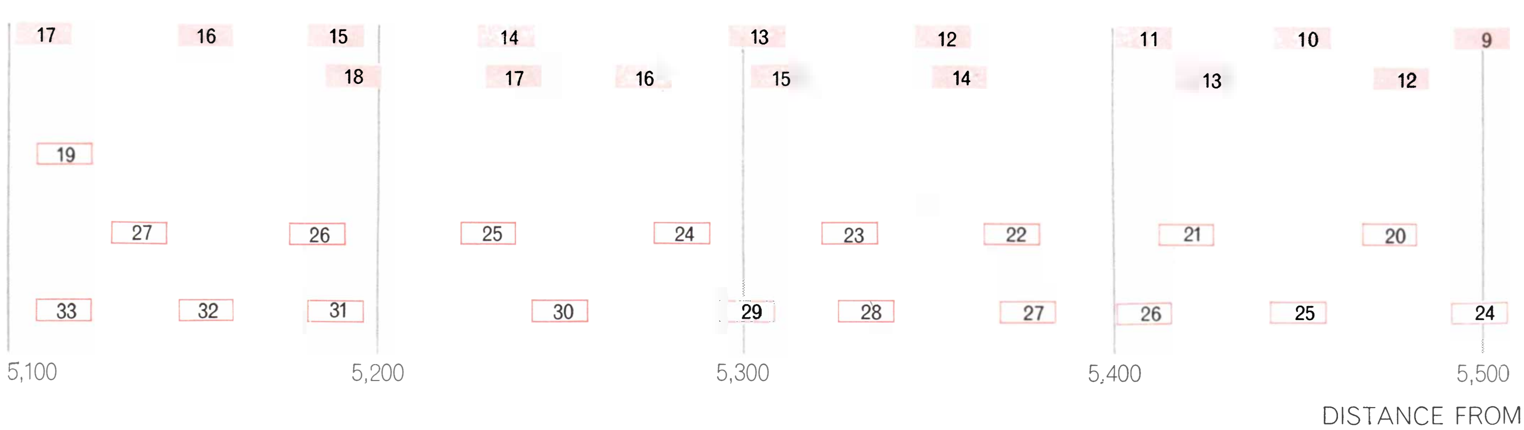
A typical bottleneck occurs on the upgrade of the Holland Tunnel's eastbound tube. Perhaps an added problem there is the fact that it is difficult to judge in a tunnel what sort of grade one is on. Whatever the causes, the area near the start of the upgrade is a frequent source of shock waves resulting from the interaction of following drivers after a leading driver has slowed.

Studying this effect of driver interactions, Harold Greenberg and other members of the Port Authority staff suggested that gaps be introduced into the traffic stream. The idea was that the gaps would provide a means of disrupting the propagation of a shock wave down a line of cars. Shock waves would still occur, but the vehicles would be moving in platoons that would have little effect on one another. Therefore each wave would be absorbed within a platoon and the over-all flow through the tunnel would be smoother. Perhaps with smoother flow the tunnel could carry more vehicles in peak periods of heavy commuter traffic.

Edie and Foote of the Port Authority conducted the first controlled experiments that confirmed this idea. They stationed an observer at the entrance of a lane to count the arriving vehicles. The aim was to keep the number of vehicles entering the lane at 44 or fewer every two minutes. These figures were based on the previous measurements of optimum flow through the tunnel. Whenever 44 vehicles entered in less than two minutes, a police officer stopped further entries until the two minutes were up. That action introduced gaps, usually of about 10 seconds' duration, in the traffic stream.

The results were dramatic. Average hourly flow, which had been 1,176 vehi-





EFFECT OF PLATOONING is depicted in these diagrams. At top a long line of cars is affected by a shock wave resulting from a momentary stopping or slowing down by car *1*; car *2* has to decelerate also, and the disturbance is propagated far back along the line, as shown in the diagram by succeeding lines representing the situation at 10-second intervals. Studying the effect of shock

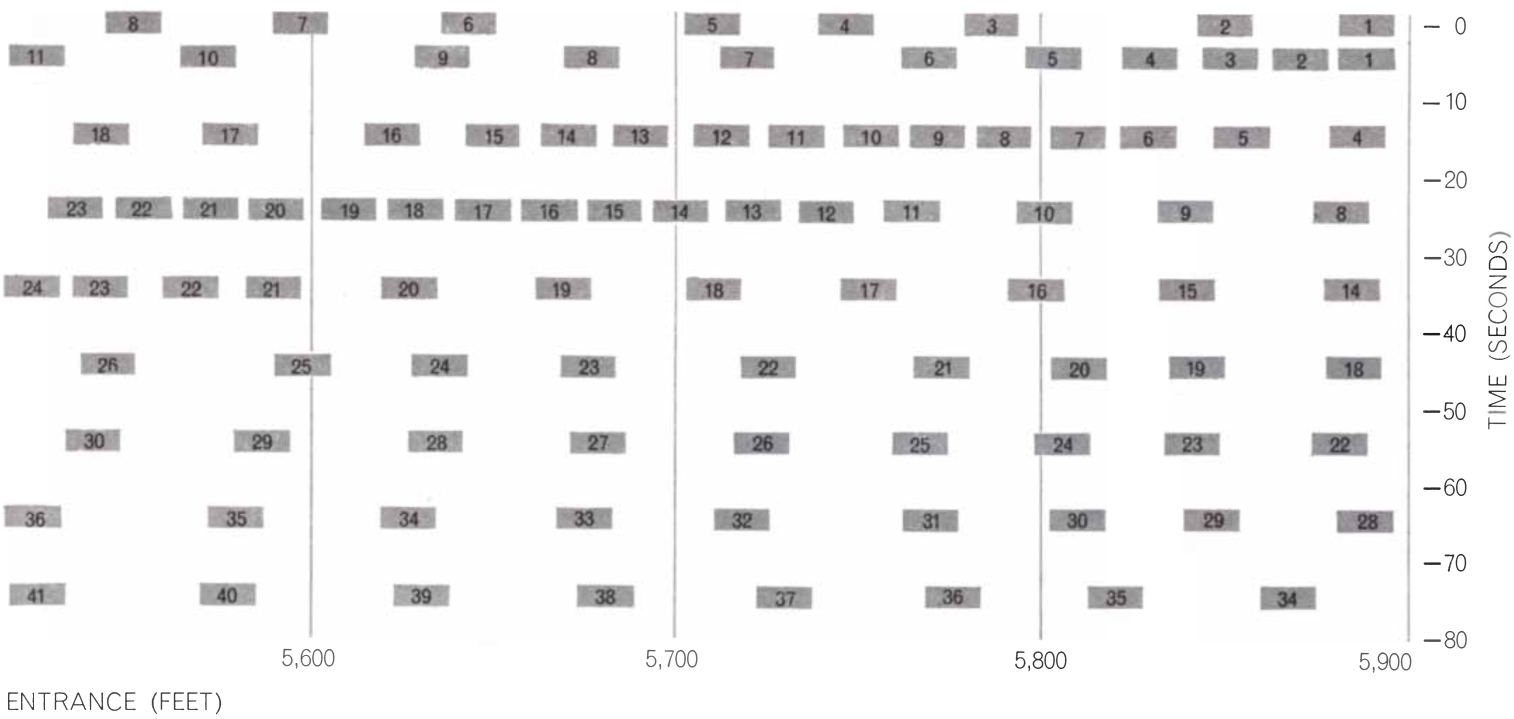
cles, rose to 1,248 vehicles with platooning. Occasionally the rate went as high as 1,320 vehicles an hour, which is about the maximum potential of the tunnel. Congestion on the tunnel approaches diminished because the flow through the tunnel was larger. Moreover, the elimination of stop-and-go driving reduced vehicle breakdowns by 25 per cent, opening the way for a still larger flow; breakdowns account for major losses in tunnel productivity. A largely unanticipated benefit was a marked reduction in tunnel ventilation requirements; there was less of the frequent acceleration that increases exhaust fumes.

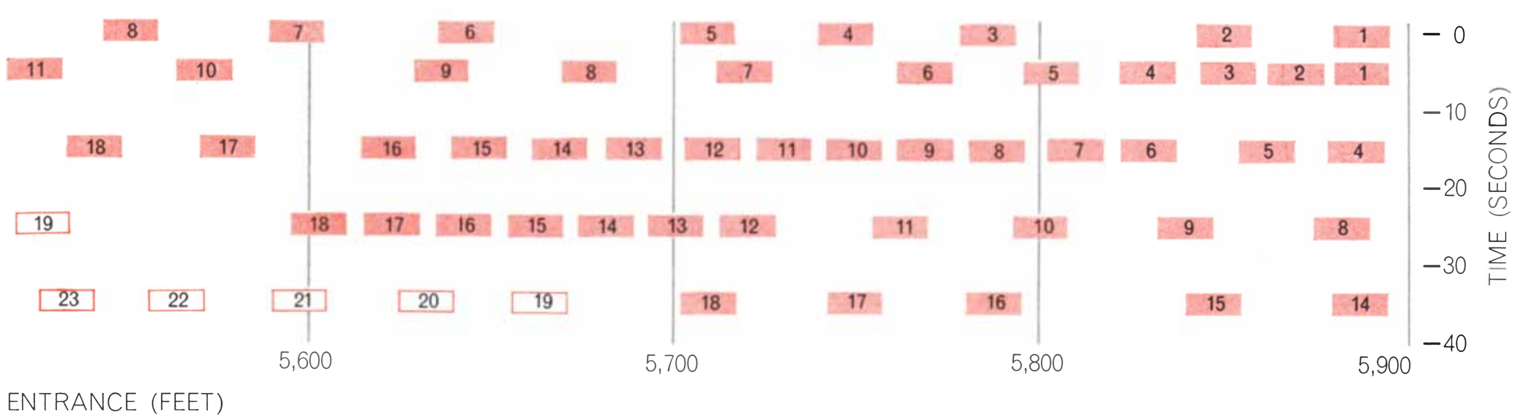
This unique traffic-control system was originally tested by means of hand signals and then semiautomatically with signal lights. It is now evolving into a fully automatic electronic system being built by Port Authority engineers for installation in the Holland and Lincoln tunnels.

Another application of traffic theory is in the study of accidents and safety. In particular follow-the-leader theory has given us some quantitative limits to a driver's sensitivity and the time lag of his response. The limits calculated by the theory suggest a criterion for distinguishing the safe driver from the dangerous one. According to this criterion a dangerous driver is one who responds too slowly or too strongly to the stimuli he receives. A driver exceeding the limits creates a condition of instability in a lane of traffic; the result may be a collision and perhaps a chain of rear-end collisions of the kind that sometimes occurs on high-speed roads.

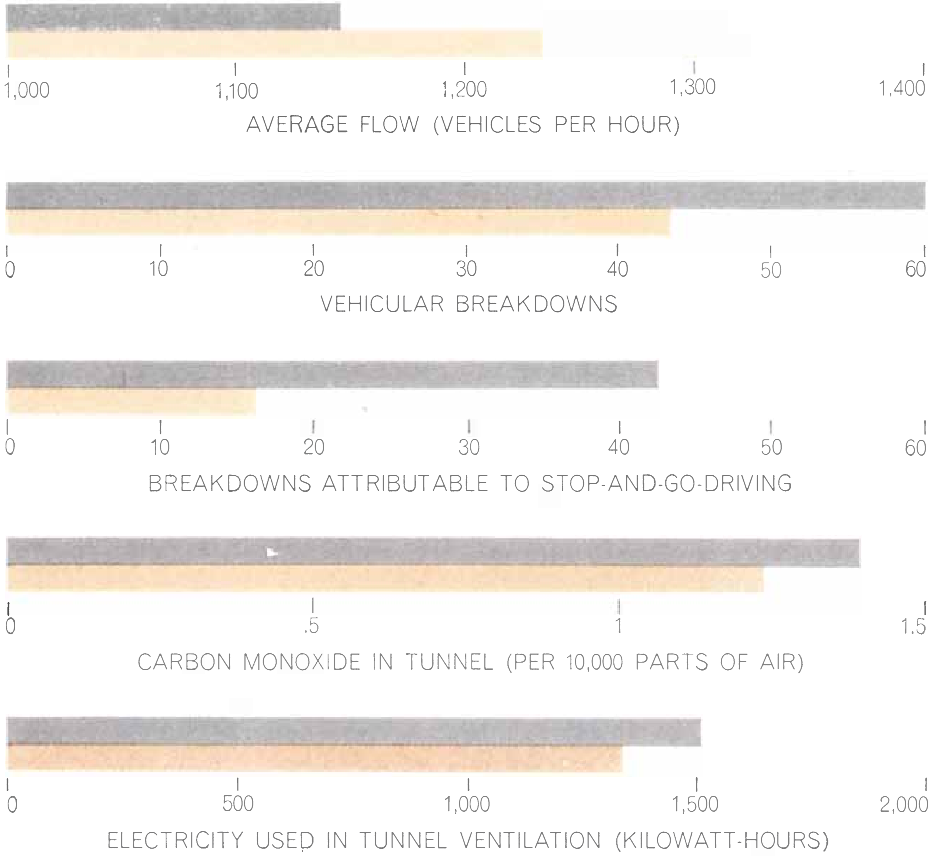
We deal with these variable characteristics of drivers as an instability factor that is the product of a driver's sensitivity coefficient and his reaction time. Assigning various values to this factor, we have made computer studies of stability. By means of these studies we have established criteria for various car-following situations that a motorist might face.

From these criteria it becomes plain that a driver with too high an instability factor—that is to say, a driver with excessive sensitivity or abnormally long reaction time—tends to amplify a deceleration pulse and to create a situation in

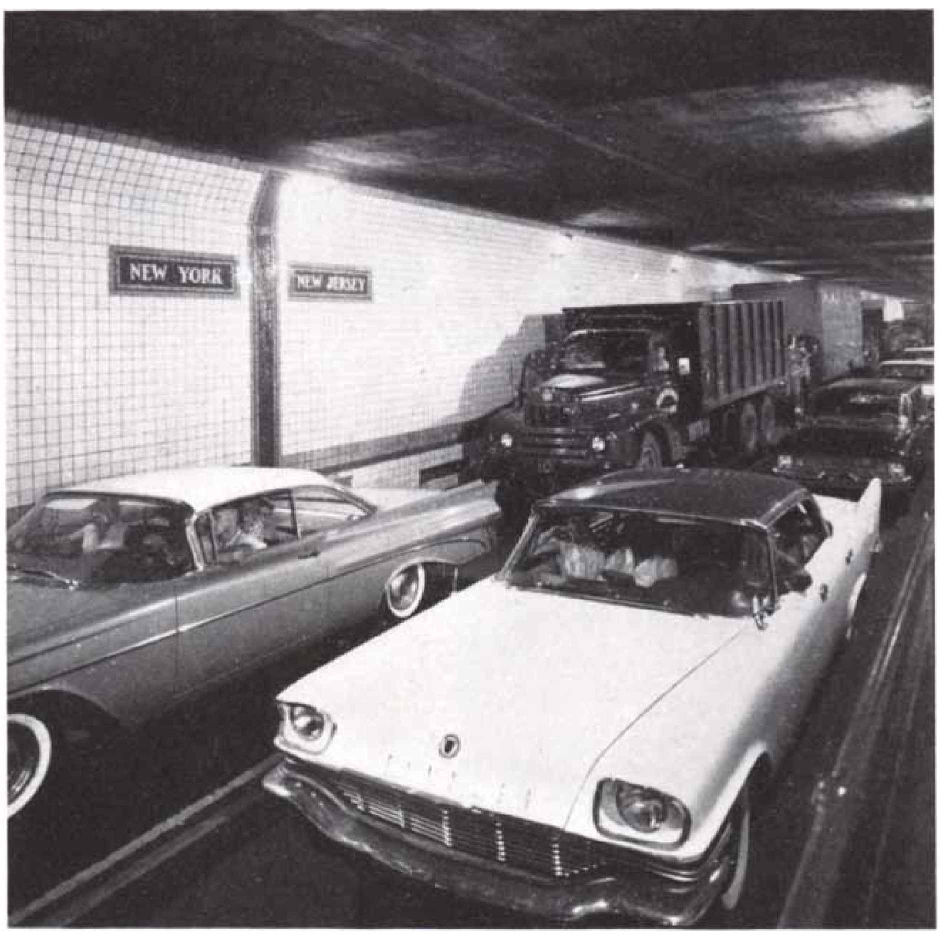




waves in the Holland Tunnel, officials of the Port of New York Authority devised a means of markedly reducing the disturbances. They formed cars into platoons by introducing gaps in the traffic. This usually confined impact of a shock wave to a single platoon, as depicted in bottom diagram, where gap appears between cars *18* and *19*. Platooning had dramatic results, illustrated on next page.



SIGNIFICANT IMPROVEMENTS in Holland Tunnel operations resulted from platooning. Colored and gray bars respectively indicate performance with and without platooning during approximately equal periods. Segment of open bar at top indicates occasional peak flow.



RUSH-HOUR LOAD typical of those carried by tunnels in the New York area is shown in the Holland Tunnel. The tunnels confront drivers with a single-lane, no-passing situation.

which an accident may occur farther back in a line of cars. Ironically it is likely that the first several cars that amplify a disturbance to accident proportions will not be involved in the actual collisions, having long since left the scene. Good drivers, for whom the product of sensitivity and reaction time is low, will tend to react in a smoother, more relaxed way to a deceleration pulse and will soak up much of the disturbance. To put the matter another way, there exists a potentially stable traffic situation if drivers control their spacing by the relative speed between vehicles, and a potentially unstable situation if they try to maintain a constant distance from the car ahead.

Our attempts to test this instability factor experimentally have been comparatively crude. However, we observed in our follow-the-leader experiments that the drivers pressed close to the outer limits of stability. It is probably true also that drivers in normal traffic are often operating on the very edge of stability.

Fortunately the instability of any single driver is counterbalanced somewhat by broader stabilizing influences that exist in highway traffic. For example, our calculations from a relatively simple car-following model indicate that the stability of a line of cars can be increased by as much as 50 per cent if each driver acts on the basis of what the car behind him as well as the one in front is doing. Moreover, as expert drivers have stressed, stability is found to increase even further when motorists watch several cars ahead and anticipate potential trouble.

Encouraged by the results of follow-the-leader theory in helping to clarify the behavior of single-lane traffic, we have begun to turn our attention toward the development of a theory relating to the behavior of multilane traffic. We proceed from the assumption, which seems safe and general enough, that automobiles in such a situation can be regarded as particles in which each driver is trying to do what he wants to but is subjected to boundary conditions.

The underlying idea of our work is a speed-distribution function: a mathematical expression that gives the distribution of speeds for all the cars and trucks on a multilane highway. In effect this factor expresses the competition between the wishes of each driver and the constraints that the environment, including other drivers, puts on him. This competition results in interactions of various drivers. The interactions can be explained mathematically by three processes.

First, the theory assumes that on a multilane highway there is a relaxation process. Given a chance, a driver does as he pleases. At low traffic concentration he will be free to do so because he will not have to interact with other drivers. All drivers, as long as they are in a position to do as they wish, will travel at their own desired speed. Traffic will achieve a desired speed distribution.

Second, if the traffic concentration is greater than zero, a vehicle will eventually come up behind another vehicle that is moving more slowly. Unlike a molecule, a driver cannot bump the driver in front up to a higher speed. He must either pass or, in heavier traffic, slow down. We describe this slowing down as a retardation, or collision, process. It leads to a decrease in the average speed of all traffic. Conversely, when a driver passes a slower car he is tending to "relax" back to his desired speed; in this instance the relaxation process has a speeding-up effect on traffic.

The third process relates to adjustment. It says that a driver is subjected to a kind of collective effect exerted by the local traffic. In heavy traffic he is forced to adjust his driving to the behavior of the cars in his immediate environment. This adjustment process, like the collision process, decreases the speed of the fast drivers. It also tends to increase the speed of the slow drivers. The net result is that it narrows the spread of the speed distribution.

From these processes we derive an equation that is similar in spirit to the fundamental Boltzmann equation of the kinetic theory of gases. Ilya Prigogine of the Free University of Brussels suggested the first form of the traffic equation and has been working closely with Robert L. Anderson and one of us (Herman) in its further development.

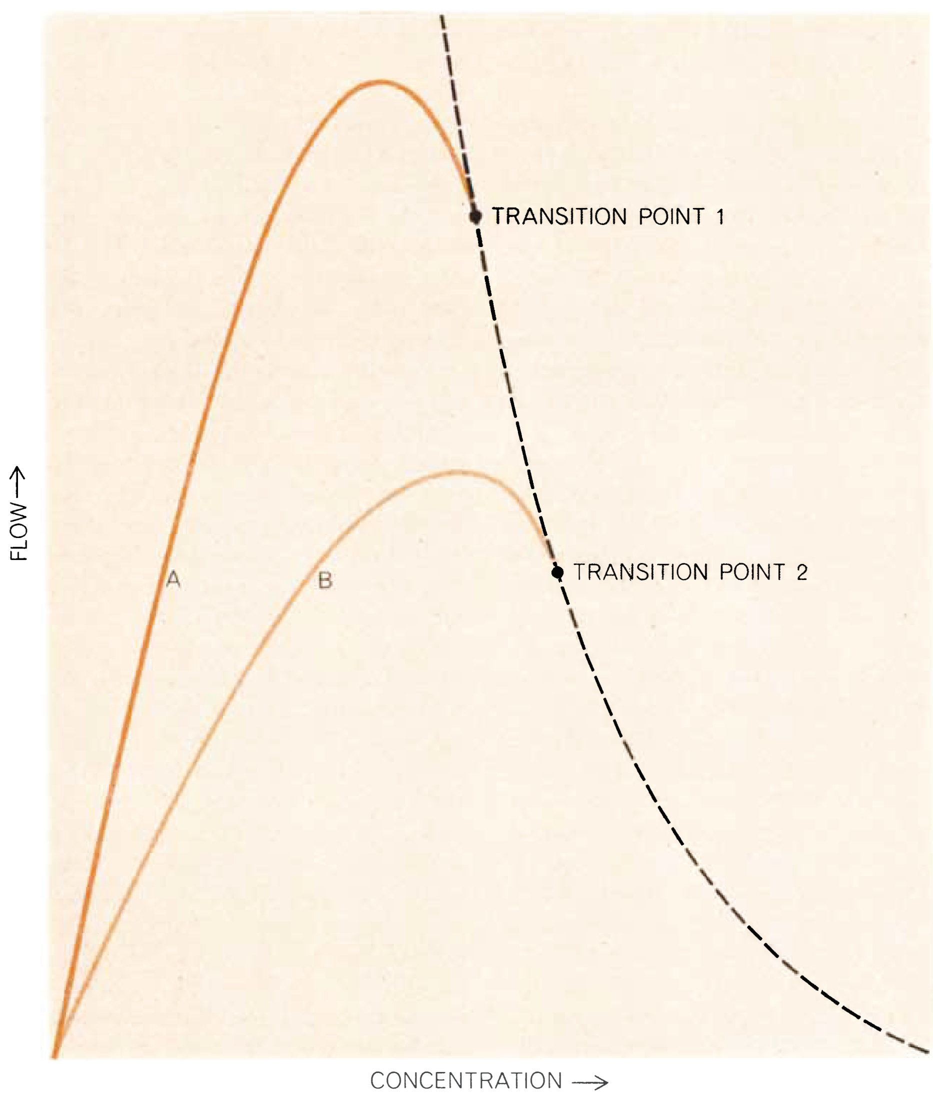
We are just beginning to collect some experimental information to compare with the predictions of this theory. Using special instruments, Rothery has assembled some preliminary data from traffic in Michigan between Detroit and Lansing on Interstate Route 96, a multilane, limited-access highway. In one section there is a five-mile stretch with no entrances or exits; it permits the gathering of data from undisturbed traffic flow.

So far we have ascertained the desired speed distribution for weekday traffic on this stretch of road; it is the distribution that occurs at virtually zero concentration. We plan to obtain data for speed distributions at various higher concentrations up to the point at which traffic is so heavy that individual cars can no longer pass because they are held to one lane.

A study of the way such a speed distribution varies with concentration predicts some interesting features of traffic. Beginning with a situation of light traffic, it is clear that a driver will do as he wishes—presumably within the limits of the law. But as the traffic concentration goes up, more and more restrictions are imposed on the driver. He must subjugate his wishes to what he can do safely—or to what he can do at all.

The theory predicts that at some critical concentration there will be a transition from individual flow to collective flow, in which traffic moves in a rather gelled state [*see illustration below*]. In that state every driver is doing what is forced on the community by the properties of this peculiar kind of fluid. During collective flow the average speed depends almost entirely on the concentration and the probability of passing. It is independent of the wishes of the drivers and therefore of the desired speed distribution. In collective flow the speed distribution is characterized by large fluctuations that indicate local traffic jams. It may be that a full understanding of speed distributions in the collective state will make it possible to predict such jams. That is a question we have not yet attempted to answer.

Indeed, there are many questions that traffic theory at its present stage of development cannot answer. We believe, however, that in time traffic theory—coupled with well-thought-out experiments and observations—will provide the basis for a science of traffic. Any insights that improve the productivity and safety of the highway complex, which represents a huge public investment, will more than repay the effort.



MULTILANE FLOW is described by an equation resembling the Boltzmann equation for a gas. Up to a point the flow is governed largely by the desires of individual drivers; here curve *A* represents a group of drivers with a higher average desired speed than group *B*. Initially the flow of both groups increases as the concentration rises; greater density restricts the flow and the curves bend. The theory predicts that at specified critical concentrations, points *1* and *2*, there will be a transition from individual to collective flow (*broken line*).