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Technology, Human Interaction, and Complexity: Reflections on Vehicular Traffic Science

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TECHNOLOGY, HUMAN INTERACTION, AND COMPLEXITY: REFLECTIONS ON VEHICULAR TRAFFIC SCIENCE

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This paper is based on the second Philip McCord Morse Lecture given May 14, 1991, at the TIMS/ORSA Joint National Meeting in Nashville. It traces the author's involvement in the development of vehicular traffic science over the last 35 years. After some historical background, the paper discusses highlights of this work: developing and testing car-following theory, traffic theory for multilane highways, the behavior of traffic in towns, the relationship of trip decisions to traffic-system dynamics, and fuel consumption in urban areas. Throughout these discussions, particular attention is paid to the role of complexity and collective effects. The paper continues with comments on the importance of viewing traffic in the context of the overall infrastructure as well as its technology and environment. It concludes with some reflections on the state of the scientific enterprise in our society.

Philip M. Morse's career and achievements are well known (see, for example, Morse 1977, Horvath and Ernst 1986). In his many roles in academia, the professions, and government he was a seminal contributor and a great leader. I first met him in the late 1930s when he was visiting the Physics Department at Princeton where I was a graduate student. My admiration for this modern Renaissance man grew over the years; I hope it is adequately expressed in the memorial tribute to him that I wrote for the National Academy of Engineering, of which he was a member (Herman 1991). I feel especially honored to present this lecture in his memory.

Like Morse and many other scientists, I became involved early in World War II with technical work associated with the war effort; this work eventually led me to operations research. My war-related activity began in the laboratory that was examining and testing the circuitry in the radio proximity fuze, a devise developed at the Applied Physics Laboratory of The Johns Hopkins University to aid naval anti-aircraft gunfire. This led me to life testing—an early effort to develop a reliability theory. I soon found my niche in responding to the challenge of service testing in the fleet. In particular, I worked on testing the anti-aircraft device in rough weather in the Atlantic Ocean and evaluating it as a shore bombardment antipersonnel weapon. I also tracked the effectiveness of the ammunition in the fleet as the dry-cell batteries in the early fuzes deteriorated with time; a reserve battery activated by the firing acceleration—the so-called setback—resolved this problem.

Later I developed a model for determining the probability of an induced firing by a proximity fuze in a multiple salvo when one of the fuzes fires prematurely. The results of this model were compared with observations.

These experiences led me to become interested in complicated problems, including those involving the complexity of human behavior. Thus, in 1956, when I accepted a position at the General Motors Research Laboratories, where there was work aimed at introducing basic science into the research efforts of an automobile manufacturing company, I felt that I might have the opportunity to explore some interesting operational problems. Before leaving the University of Maryland, I had fruitful discussions with the late Elliott W. Montroll about the type of research one might do that would be relevant to the institution and also scientifically interesting. Our wide-ranging experiences in science suggested that it would be fascinating to explore an operational area then new to

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science: vehicular traffic, that is, how human beings interact through a machine—the automobile. At that time, the science of vehicular traffic was only at its inception.

This paper recounts how our work on vehicular traffic, including some of its human aspects, evolved. After some historical background, it discusses various highlights of the research, including the roles of complexity and collective effects. This work extended over a period of about 35 years, and involved the collaboration of a number of outstanding colleagues from various parts of the world. The paper continues with some comments about the importance of viewing traffic in the context of the overall infrastructure, as well as the technology and environment. It concludes with some personal reflections on the state of the scientific and technical enterprise in our society.

INTRODUCTION

Vehicular transportation and its related traffic problems involve the interacting man-vehicle-road complex; the rules of the game are spelled out, but only in part, by laws and social customs.

The city has been crowded for a long time; traffic congestion is an age old problem. In ancient Rome, where the population has been estimated at many hundreds of thousands, there were acute traffic problems; thus, the assignment of priorities exemplified by what we read in the *Corpus Inscriptionum Latinarum*:

> Let no one after the Kalends of January drive or conduct a wagon between the time of sunrise and the tenth hour of the day along those streets which lead or will lead into the city of Rome in the regions where there is populous habitation, unless it be necessary that material be carried or transported for the sake of the building of sacred temples of the immortal gods, or for the sake of public works, or unless it be necessary that materials that have been publicly contracted for demolition be carried out from the city or from these regions, on the condition that permission shall have been granted through this law to specific men in specific cases to drive or conduct wagons for this process (Crook 1967).

How modern all this seems!

We also read with dismay about the state of the roads in London in the 17th century, especially during the time of the great fire, when narrow streets turned by rain into quagmires made the movement of fleeing people and their carts, loaded with worldly possessions, virtually impossible. Near the middle of the 18th century, Lord Hervey wrote from Kensington, not far from London, lamenting that,

> ... the road between this place and London is grown so infamously bad that we live here in the same solitude as we would do if cast on a rock in the middle of the ocean; and all the Londoners tell us that there is between them and us an impassable gulf of mud (Smiles 1968, p. 163).

The trip by coach between London and Edinburgh took 6 days or more; between Bath or Birmingham and London it took about 2–3 days as late as 1760. The rate of travel was about 6 miles per hour; the work "tore the horses' hearts out," and traveling was a source of danger and great suffering for the traveler. Toward the latter part of the last century, before the automobile, we begin to have photographic evidence of traffic jams, in Philadelphia and New York City, for example, that stagger the imagination even by recent standards. These growing social problems were encountered when that "awful horse," a serious source of disease, was responsible for about 80% of the road accidents (The Motor World 1901).

The importance of mobility and freedom of communication have long been appreciated, as was so eloquently expressed by Samuel Smiles in 1862:

> Freedom itself cannot exist without free communication,—every limitation of movement on the part of the members of society amounting to a positive abridgement of their personal liberty. Hence roads, canals, and railways, by providing the greatest possible facility for locomotion and information, are essential for the freedom of all classes, of the poorest as well as the richest (Smiles, p. 156).

It is unfortunate that the continual phenomenal burgeoning of traffic carries with it serious personal and social ills that still have not been fully matched by our level of fundamental understanding of vehicular traffic science or by our will to apply what is known. Over the long and distant past the primary concern was with town planning for security and efficiency, as well as with road building. However, the strong interconnection between traffic and town planning was recognized by such inquiring minds as Leonardo da Vinci who, concerned with this important but vexing aspect of life, recorded in this notebooks, an imaginative two-level city conception:

> And know that if anyone wishes to go through the whole place by the high-level roads, he will be able to use them for this purpose, and so also if anyone wishes to go by the low-level roads .... The high-level roads are not to be used by wagons or vehicles such as these but are solely for the convenience of the gentlefolk. All carts and loads for the service and convenience of the common people should be confined to the low-level roads (McCurdy 1935).

At present, there are an increasing number of cities around the world with populations approaching ten to twenty million. With the proliferation of motor vehicles overreaching the capacity of streets and highways, many third-world cities such as Seoul, Rio de Janeiro, and Taipei have a daily rush hour that stretches to more than half the day. As a consequence, people and the environment pay a heavy penalty. It is imperative that we address this problem with a sensitive realization that traffic and transportation are a part of the overall infrastructure, so that we approach the entire system from an operations research point of view. Of course, we need better engineered cars, more mass transit, considerably improved overall urban design and more technically sophisticated traffic management. However, we must continue to focus on the science of traffic, theoretical, experimental, and particularly observational, to create the foundation on which we can build the practical know-how that will allow us to alleviate our increasingly difficult problem of urban congestion.

The Feasibility of a Traffic Science

One of the ultimate goals of traffic science must be to understand and describe quantitatively the character of traffic in large city street networks. Until recently, it has not been easy to comprehend how this might be achieved on a purely microscopic basis, since it would clearly require knowledge concerning the movement of all the vehicles on all the links and through all the nodes of the network system under consideration. With the advent of the supercomputer this goal appears on the horizon. It is not inconceivable that an intelligent vehicle highway system might contain information on the location, speed, and destination of all the vehicles in a relatively large street network, and then direct the traffic in detail on the basis of some methodology to achieve a predetermined overall goal.

On the other hand, there is also the hope that an examination of the averages of some pertinent variables in such a highly complex system might lead to simple functional relations. Such simple relations can result from collective effects; that is to say, many of the variables are highly correlated. In this connection it is interesting to recall that in 1911, John Muir, the American naturalist, in his book *My First Summer in the Sierra* wrote: "When we try to pick out anything by itself, we find it hitched to everything else in the universe" (Muir 1911).

Problems of this type, in which there are many nonlinearly interdependent variables, that is, problems complex in the interrelational sense, have been termed symplectic problems. The word symplectic derives from the Greek word *symplektikon* meaning intertwined or complex, precisely in the interrelational sense. Many problems in the physical, biological, and social sciences are now known to be of this type and special methodologies are being sought to handle them. In particular, there has been a revolution in these sciences brought on by studies in nonlinear dynamics of systems exhibiting chaotic behavior. Until the 1960s it was assumed that the behavior of classical mechanical systems could be predicted accurately by assuming the existence of deterministic equations describing the evolution of the system and by specifying initial conditions. However, chaotic systems appear to be random because they are extremely sensitive to the initial conditions. Two starting points, no matter how close initially, will generate solutions that will eventually diverge. Unless the initial conditions are known with impossible infinite accuracy, such systems are inherently unpredictable!

It is fascinating to contemplate that humans have an innate propensity to create mental models which, in the final analysis, are simply our view and interpretation of some aspect of the world. Perhaps the earliest models focused on cosmogony and led to mythological conceptions. On the technical side they range from physics to engineering and sociotechnical systems in order of increasing complication. Prior to the turn of this century physical science was primarily concerned with two-variable problems of simplicity. Starting with Boltzmann and Gibbs near the end of the last century an attack was made at the other extreme. Physical scientists and mathematicians developed methods employing probability theory and statistical mechanics which could deal with an astronomical number of variables and which address problems that have been termed disorganized complexity.

It is in the middle range, involving a considerable number of variables, that we observe organized complexity, which is the most troublesome to understand and model with any confidence (Prigogine, Allen and Herman 1977). This is so in spite of the remarkable effectiveness of mathematics in the natural sciences. Moreover, in this intermediate regime, especially when the human element is present, precise measurements are not possible. This is unlike physics, where it has been traditional to reach for ever greater precision because, as aptly stated by F. K. Richtmeyer long ago, " . . . the whole history of physics proves that a new discovery is quite likely to be found lurking in the next decimal place" (Richtmeyer 1932). However, the great power of the supercomputer now allows the exploration of solution spaces hitherto inaccessible, which opens up the possibility of visualizing new pathways in problems of great complexity.

The traditional success in modeling classical problems in physics has perhaps led us to believe that we can be as successful in modeling problems of increasing complexity, even those involving human interaction. However, a distinction between physical systems and those including human beings must be drawn; in general, physical systems have considerably lower complexity than human systems. It must be borne in mind that systems in which the rules are fixed, such as is the case in physical systems, can be relatively simple, whereas systems involving human beings expressing their microgoals, which may vary during some processes, can exhibit incredible model complexity. From this point of view, chaotic systems that may appear random actually exhibit beautiful overall regularities, precisely because they are controlled by deterministic differential equations.

TRAFFIC-FLOW THEORY AND RELATED PROBLEMS

One might say that the science of vehicular traffic started in 1936 with a paper titled "Road Traffic Considered as a Random Series" by William F. Adams (1936). This work was followed by a highly seminal paper in the early 1950s by Wardrop (1952), "Some Theoretical Aspects of Road Traffic Research." At this time, Reuschel (1950a, b, c) and Pipes (1953) each contributed papers on car-following models which did not include time lags and therefore could not address the stability question. Another fundamental paper in 1955 was that of Lighthill and Whitham (1955): "On Kinematic Waves: A Theory of Traffic Flow on Long Crowded Roads." At this same time, an interesting approach was developed in Newell's (1955) paper, "Mathematical Models for Freely-Flowing Highway Traffic." These and subsequent works to be discussed began to create the foundations for a science of vehicular traffic.

The Theory of Traffic Flow

During 1956, Montroll and I conceived a theoretical basis for describing the dynamical behavior of a platoon of vehicles on a single-lane highway, with no passing, in terms of human behavior (Chandler, Herman and Montroll 1958; for a selected bibliography, see Herman 1966 and 1982). This led to our theory of car following which, stated simply, says that the acceleration response of a driver in a platoon of vehicles at the time $(t + T)$, where T represents the time lag, is proportional to the relative speed with respect to the nearest neighbor vehicle ahead at the time t multiplied by a so-called gain factor that is equal to a sensitivity coefficient divided by the spacing between the two vehicles. The sensitivity coefficient is a measure of how large a response is generated by the driver when confronted with an external stimulus, namely, a relative speed. It is assumed that the rational driver wishes to keep up with the car ahead in a safe manner.

Various mathematical formulations of these simple ideas have been discussed over the years; I will now indicate how this result was achieved. If the driver's next-nearest neighbor forward and nearest neighbor behind are ignored in the present discussion for the sake of simplicity, we can fix our attention on the most basic case of interactions with the forward nearest neighbor only and write in general form the following stimulus-response equation:

$$\frac{d^2x_n(t+T)}{dt^2} = \lambda\left[\frac{d^p x_{n-1}(t)}{dt^p} - \frac{d^p x_n(t)}{dt^p}\right], \tag{1a}$$

in which λ, the gain factor, is considered a function of speed and spacing, namely,

$$\lambda = \lambda_{l,m}\left(\frac{dx_n(t)}{dt}\right)^m \Big/ [x_{n-1}(t) - x_n(t)]^l \tag{1b}$$

and the parameter $\lambda_{l,m}$ is termed the sensitivity coefficient (Gazis, Herman and Rothery 1961).

This equation states that the acceleration of the nth vehicle is proportional to the difference of the pth time derivatives of the positional coordinates of the nth and $(n - 1)$st vehicles. While it is an oversimplification to assume that the car-following task can be described properly in terms of a continuous differential difference equation, this approach has led to very useful results. Moreover, the equation implies that after mental processing the driver responds at the time $(t + T)$ only to the stimulus information received during the time interval dt at t. This aspect of the problem can be improved from a theoretical point of view by introducing memory functions.

One of the main interests in car-following theory is to examine questions of stability and the type of steady-state flow characteristics that the theory implies. With respect to the car-following task I suggest that a driver can hardly estimate the physical quantities represented by values of the parameter p greater than unity (for example, acceleration, jerk, etc.). In addition, note that following the car ahead by means of estimating the relative spacing, i.e., $p = 0$, can be shown theoretically to be inherently unstable. Both of these points were verified by experiment. In general, it can be shown that solutions with p even are all unstable, while solutions with p odd are inherently asymptotically stable. Thus, the observational data were well represented by means of a car-following equation of the form:

$$\frac{d^2x_n(t+T)}{dt^2} = \lambda\left[\frac{dx_{n-1}(t)}{dt} - \frac{dx_n(t)}{dt}\right], \tag{2a}$$

with

$$\lambda = \frac{\lambda_{1,0}}{[x_{n-1}(t) - x_n(t)]}. \tag{2b}$$

On the basis of this simple stimulus-response model it was possible to determine for the linearized case (λ = constant) an asymptotic stability criterion, namely,

$$\omega/\lambda > 2 \sin \omega T, \tag{3a}$$

in which ω is the monochromatic frequency of the perturbation (Herman et al. 1959). Asymptotic stability is ensured for all frequencies so long as inequality (3a) is satisfied. For the values of ω within the low-frequency range of vehicular traffic oscillations, the product λT has a small range of values of about 0.50 to 0.52 that satisfy stability. In the case where $\omega \rightarrow 0$ we have the simple result

$$2\lambda T \leqslant 1, \tag{3b}$$

which shows that the stability of a platoon of vehicles depends on human behavior as specified by two parameters, a gain factor λ and a time lag T. In addition, the theory with λ inversely proportional to the spacing yields a relation between the flow and concentration which interestingly has a maximum when the traffic is moving at an average speed equal to the sensitivity coefficient (Gazis, Herman and Potts 1959).

Car-Following Theory and Experiments

The spirit of our early work was to create a theoretical model, to design and conduct experiments to validate the model, and, particularly, to obtain data to learn what nature was saying. It is fascinating that in this complex problem it is still possible to obtain simple results concerning specific aspects of stability and flow. One might ask, since models must be validated, how can theory be compared with experiment and observation? It is interesting to recall that when we first started this work we were discouraged from pursuing the experimental and observational aspects of car following with the statement that we should confine our attention to theory and that the engineers would then do the rest. It is fortunate that we were able finally to work on all aspects of this problem. That is often the best way to generate progress in what is essentially an experimental science.

Let us now examine this question for the simple car-following case where the acceleration of the following vehicle is proportional to the relative speed between it and the nearest forward neighbor. For the sake of simplicity, in this discussion let us assume that the proportionality coefficient, that is, the gain factor λ, is a constant. We arranged for a lead driver to go through some programmed speed maneuvers and for the following driver to follow in a normal safe manner. Using appropriate instrumentation it was possible to record in detail the time histories of the dynamical variables for the two vehicles involved. These data provided us with the position, speed, acceleration, and relative speed, all as functions of time, for each of the vehicles.

It was then feasible to perform a linear correlation analysis using the simple linear car-following equation in which T is the time lag and λ is the constant gain factor, which tells us how much a driver does in response to a given relative speed stimulus. The idea is to determine the correlation coefficient between the acceleration of the following vehicle and the relative speed of the two vehicles for selected values of the time lag. When this is done for a series of time lags the correlation coefficient has a maximum at some particular time lag, which is taken as the time lag of the following driver. The statistical procedure also tells us that the coefficient λ is equal to the maximum correlation coefficient $r_{\max}$ multiplied by the ratio of the standard deviations of the acceleration and the relative speed, that is,

$$\lambda = r_{\max}[\sigma(a)/\sigma(u_{\text{rel}})]. \tag{4}$$

In this manner, it is possible to obtain the time lag and the sensitivity coefficient for various drivers in a real-world situation. Interestingly, it turns out that the drivers of passenger cars have values of this pair of parameters that imply they are driving on the margin of stability. In contradistinction, the values of these same parameters for drivers of heavy vehicles, such as trucks and buses, in similar car-following experiments imply that these drivers are operating well within the region of stability and are rarely close to the instability bound. This result in itself is fascinating in that it shows that human beings often push to the limits of a given task.

Moreover, as mentioned earlier, when the model is refined by taking into account that λ varies inversely as the intervehicle spacing, the flow q can be expressed in terms of the concentration k and the speed u as

$$q = uk = -\lambda_{1,0} k \ln(k/k_j), \quad (5)$$

where k_j is the maximum or so-called jam concentration. Equation (5) yields the result that when maximum or optimal flow is achieved, that is, $dq/dk = 0$, the average speed of the traffic is equal to the sensitivity coefficient $\lambda_{1,0}$. It is significant that the average value of the sensitivity coefficient, which is actually a different microquantity for different people, provides information about the collective macroquantity flow. Thus, we have a connection between the micro and macro traffic worlds showing that the detailed behavior of people in the car-following mode, for example, on a single lane of a tunnel with no passing, determines the condition under which the overall flow will be a maximum. The maximum flow in the Holland Tunnel occurred at an average speed of about 18 mph corresponding well to the value of the sensitivity coefficient determined by car-following experiments performed in that tunnel with many different drivers.

It is well known that for concentrations beyond the peak of the flow-concentration curve the observed flow fluctuates rather widely. This phenomenon has been explained in terms of statistical hydrodynamic considerations, which show that, for sufficiently high concentrations, long-wavelength perturbations produce instability in the flow (Balescu et al. 1967). More recently, it has been suggested that the instability can be described in terms of chaotic behavior.

Another aspect of this problem is exemplified in vehicular tunnel traffic. If one determines the level of "speed noise" (dispersion of the speed distribution function) in terms, say, of the average of the absolute value of the relative speed between successive vehicles, then a plot of this quantity versus the average speed exhibits a rather broad minimum. It is intriguing that the minimum occurs essentially at the speed for which the flow-concentration curve is a maximum. We found that embedded in the description is the idea that smooth traffic is most efficient traffic. Thus, it would be best if everyone drove in a manner similar to the vehicles in their local vicinity.

Returning to a platoon of vehicles moving in a tunnel at constant speed, we find that the "acceleration noise" associated with the lead vehicle is quite small, increases along the platoon and saturates at about the fifth or sixth vehicle. When the lead vehicle makes a speed-changing maneuver, the fluctuations around the new speed increase significantly as one moves to successive vehicles. At low speeds the amplification of the speed noise often leads to stoppages, to the surprise of drivers perhaps ten cars away from the initiation of the maneuver!

Multilane-Highway Traffic-Flow Theory

When I next turned my attention to the problem of vehicular traffic, it was for a multilane highway as opposed to a single lane. Here it was not clear how to take into account the influence of the time lag. It was then that I discussed the problem with Ilya Prigogine, realizing that he was an expert in statistical physics. He quickly became interested in this problem, even though many of my physicist colleagues had already suggested that problems in vehicular traffic would unquestionably lead to a statistical morass; they were wrong!

It is exciting now, many years later, to recall that Prigogine suggested a model based on a Boltzmann-like equation to describe the evolution of the speed distribution function of the cars on a multilane highway (Prigogine and Herman 1971). This is a nonlinear integrodifferential equation in the unknown distribution function in which the average speed and concentration of the vehicles depend implicitly on the distribution function itself. Thus, a kinetic theory of vehicular traffic has been developing for over a quarter of a century to attempt to describe the characteristics of traffic on multilane highways.

In this theory we have examined the evolution of the speed distribution function in terms of a number of important processes: a relaxation or speeding-up process, which expresses the attempts of drivers to achieve their own desired speeds, that is, microgoals, by passing slower cars; an interaction or slowing-down process, which arises in the conflict between a faster driver and a slower driver; and an adjustment process, which reduces the variance around the local mean speed. On the other hand, we tried to avoid examining many specific details—for example, the detailed description of all the vehicles in queues and the dynamics of passing maneuvers.

Let us examine the mathematical structure briefly in order to have a better idea of the theoretical formulation. If we let the speed distribution function f be designated as a function of position x, speed v, and time t, then we can write for the evolution of this speed distribution function

$$\frac{df(x, v, t)}{dt} = \frac{\partial f}{\partial t} + v\left(\frac{\partial f}{\partial x}\right) = \sum_i \mathscr{P}_i, \quad (6)$$

where $\mathscr{P}_i$ represents the various processes discussed above.

The relaxation process can be expressed in the form

$$\left(\frac{\partial f}{\partial t}\right)_{\text{rel}} = -(f - f_0)/T, \tag{7a}$$

where f_0 is the desired speed distribution function and the relaxation time T is assumed to be the following function of the probability of passing P, with τ an empirical parameter:

$$T = \tau(1 - P)/P, \tag{7b}$$

so that

$$\left(\frac{\partial f}{\partial t}\right)_{\text{rel}} = -(f - f_0)P/[\tau(1 - P)]. \tag{7c}$$

The interaction process leads to the following result:

$$\left(\frac{\partial f}{\partial t}\right)_{\text{int}} = \sum_{ij} (\Gamma_{ij}^{(+)} - \Gamma_{ij}^{(-)})(1 - P) = fc(\bar{v} - v)(1 - P), \tag{8}$$

where the quantities $\Gamma^{(-)}dxdvdt$ and $\Gamma^{(+)}dxdvdt$ represent the numbers of cars subtracted and added to $dxdv$ by interactions between the various cars in the time dt, $\bar{v}$ is the average speed, and the other quantities are defined as above, with the exception that now the concentration is denoted by c in order to conform to the notation employed in the original literature.

The adjustment process, which at higher concentrations is somewhat similar to the car-following process in that it tends to cluster the speeds of cars in a local environment around the mean, can be written in the form

$$\left(\frac{\partial f}{\partial t}\right)_{\text{adj}} = \lambda'(c)(1 - P)c[c\delta(v - \bar{v}) - f], \tag{9}$$

where $\delta(v - \bar{v})$ is the Dirac delta function and λ' is a parameter that is a function of the concentration c.

The model, simple though it was, already had rather realistic features embedded in it, such as an individual regime in which drivers, to an extent depending on the concentration, could act independently to achieve their microgoals, and another, a collective regime, in which the behavior of the traffic no longer depends on the desired speeds of the individual drivers, thus revealing a phase transition. In this collective regime, the average speed of the cars depends on the concentration, as well as on the probability of passing, and the relaxation time (both of which are themselves functions of the concentration), but not on the desired speed-distribution function. It was also possible to show that the first-order deviations from the linear portion of the flow-concentration curve at low concentrations are determined by the dispersion of the desired speed-distribution function and are proportional to the cube of the concentration. This high-power dependency is the result of collective effects. The model was subsequently developed more fully and was tested successfully some years later by observations of the multilane traffic on the New Jersey Turnpike (Herman and Lam 1971a, b, Edie, Herman and Lam 1980).

Characterizing Urban Traffic

Since the beginning of this work we had been searching for an extension of the kinetic theory of vehicular traffic that would describe in a similar overall fashion the traffic in towns, that is, traffic circulating on an extended urban street network. During the latter part of the 1970s I had been examining all the data I could find relating to the character of urban traffic. These data consisted in part of about twenty thousand miles of speed-time histories from chase-car observations in nine cities in the United States. They began to reveal remarkable regularities in the speed-distribution function as a function of concentration, the variance of the speed, and the variance of the acceleration as functions of the speed, and perhaps most interesting of all, an essentially linear relation, although slightly convex upwards, between the observed trip time and stop time per unit distance for a vehicle circulating in an urban street network.

Prigogine and I again collaborated and developed what we termed a two-fluid model of town traffic as a consequence of our trying to understand the simple trip-time/stop-time relation (Herman and Prigogine 1979, Chang and Herman 1978). The concept of a two-fluid model had already appeared in our kinetic theory of multilane highway traffic twenty years earlier when the transition to the so-called collective flow regime was achieved at sufficiently high vehicular concentrations. We found that the average speed depends on the fraction of the cars that are immobilized. At the collective transition, the speed-distribution function for cars splits into two parts, one corresponding to the moving vehicles and the other vehicles stopped as a consequence of congestion, traffic signals, stop signs, and barricades, but not in the parked condition.

Extending the ideas in our kinetic theory of traffic, we assumed that the average speed v_R of the moving cars depends on the fraction f_R of cars that are moving according to a power law, for example,

$$v_r = v_m f_R^n, \tag{10}$$

where v_m is the average maximum speed and n is a parameter to be determined from observation. In addition, we expected that the fraction f_s of vehicles stopped could be equated to the fraction of the time stopped for a car circulating in the street network:

$$f_s = T_s/T, \qquad (11)$$

where T_s is the stop time per unit distance, T is the trip time per unit distance and $f_R + f_S = 1$. This statement, equation (11), can be considered as a type of ergodic or at least a quasi-ergodic condition. These two relations led to a simple transcendental equation relating the stop time to the trip time, each per unit distance:

$$T_s = T - T_m^{1/(n+1)} T^{n/(n+1)}, \qquad (12)$$

where $T_m = 1/v_m$. While this relation is nearly linear it is actually slightly convex upwards in conformance with the observations.

During the past ten years we have applied these ideas to traffic in many cities around the world and have been able to verify the theoretical basis with observations as well as experiments carried out in various urban street networks (Herman and Ardekani 1984, Ardekani and Herman 1985, 1987). It is important to point out that several hours of data are sufficient to determine the two-fluid parameters, T_m and n for the urban street network of a typical central business district in most cities. This work has enabled us to make quantitative assessments of the relative quality of the traffic and the traffic systems in a large number of cities in the United States and abroad, a most practical consequence of these theoretical ideas. What is perhaps most important in this connection is that here again we have a nonlinear problem of great complexity with many variables that can be organized by recognizing certain relatively simple properties of the system. One of the main driving forces in determining what happens in traffic in a street network is the way people behave, coupled with the constraints of the street geometry, traffic control system, weather, grades, and the like. This gives us the hope that such complex systems involving human beings can be represented in some stochastic sense if not precisely.

The development of the two-fluid model to characterize the performance of traffic in urban networks in terms of the interrelation among descriptors defined at the network level has been validated, as described above, by using test cars circulating in the traffic, by chase-car studies, and to a limited extent by analyzing aerial-photographic data, all of which are resource intensive approaches. For this reason, it was highly productive to collaborate with Hani S. Mahmassani and a number of his graduate students at The University of Texas at Austin in microscopic simulation of vehicles circulating in networks under controlled conditions. This work has provided an important supporting tool for the further development and extension of theory, especially the dependence of the proposed relations among network-wide variables on the topological and operational features.

Studies along these lines started some years ago with the examination of a 5 × 5-node network and proceeded to progressively larger networks up to an 8 × 8-node network, as well as to a simulation of the Austin Central Area Network consisting of 1,600 links with 256 lane-miles, using only about 30% of the memory capabilities of a CRAY supercomputer (Mahmassani, Williams and Herman 1987, Mahmassani, Jayakrishnan and Herman 1990). In addition to demonstrating the feasibility of performing microscopic simulations of large networks, a broad spectrum of possibilities has become available for simulation-based studies of real urban traffic networks; such work can support the development of network-level traffic theory. These studies have been effective in characterizing the quality of urban traffic in networks of different sizes under a variety of control strategies. It has now become possible in large networks to study the influence of different types of signalized control, the effect of extreme congestion, the impact on the traffic system of short and long-term events which occur as the result of accidents and construction, and many other situations of practical and theoretical interest.

Another important area of great practical interest at the present time concerns strategies for electronic route guidance. The integration of the largely available telecommunications and microprocessor hardware technologies for the purpose of providing real-time information to vehicles is now being developed in various countries. Important systems questions regarding the type and frequency of supplied information and the extent of its availability to network users are being addressed. Microscopic simulation clearly provides an important technique for evaluating the effectiveness of various strategies for vehicle guidance, but to conduct such studies a considerable amount of additional knowledge is required, especially on the user's route choice when provided with different types of information.

Trip Decisions and Traffic System Dynamics

In this connection it is important to mention another body of work concerning the interaction of trip decisions and traffic system dynamics also carried out in collaboration with Mahmassani (Mahmassani and Herman 1987, 1990). Vehicular traffic systems are highly complex systems in which individual tripmakers experience outcomes of their own decisions that are nonlinearly related to the decisions of a large number of other tripmakers. This interaction is especially evident in the peak-period home-to-work commute. The day-to-day congestion in the various transportation facilities is a consequence of the time-dependent usage patterns of the commuters; it results from the large number of individual decisions with regard to departure time, routing through the network, mode of travel, and other choice dimensions; on the other hand, these decisions may change from day to day, due largely to the congestion experienced by the commuters.

The research has addressed the following objectives: to formulate a theoretical framework for explaining the day-to-day departure decision dynamics of commuters, to identify mechanisms by which users adjust these decisions in response to congestion, and to characterize the evolution and dynamic properties of traffic commuting systems, particularly under alternative behavioral mechanisms operating at the individual level.

It is essentially impossible, in the present commuting context, to obtain real-world information at an appropriate level of richness. An alternative adopted in this work has been to perform controlled experiments involving real commuters in a simulated traffic system. The human participants independently supply departure time decisions, which are then entered into a computer simulation model of traffic flow. Various forms and levels of feedback are supplied to the participants about the outcomes of their decisions, and then new decisions are sought for the next day, and so on for as many days as might indicate convergence. Such experiments, in which actual human subjects are the decision makers in a computer-simulated traffic environment, have opened fruitful avenues for exploring the interaction between trip decisions and traffic system dynamics.

Fuel Consumption in Urban Areas

A final example of a simple result obtained for a very complicated problem is the fuel consumed per unit distance by an automobile powered with a gasoline combustion engine traveling in an urban street network (Evans, Herman and Lam 1976a, b, Chang et al. 1976). In spite of a very large number of pertinent factors, we found many years ago that the fuel consumed per unit distance depends linearly almost entirely on one variable, the trip time per unit distance; the explanatory power is increased if the deviation of the number of stops per unit distance from the average value is also taken into account (Chang and Herman 1981, Herman and Ardekani 1985). In this case, we initially found the simple linear relation empirically by making field observations and then were able later to show theoretically that the basic result could be derived from the known energy equations for the automobile combustion engine and drive train.

In connection with these studies we have also examined the influence of driver behavior on fuel consumption as well as on the overall character of the driver's speed-time history and safety (Chang and Herman 1980). In general, compared to the way most people drive, conservative driving saves some fuel but with a trip-time penalty. On the other hand, for aggressive driving the trip time is reduced but with an associated increase in fuel consumption that grows markedly with the driver's acceleration noise.

It is difficult to evaluate driver behavior quantitatively using simple variables such as trip time or average speed. However, we have studied detailed speed-time histories and obtained information concerning how different drivers behave under similar traffic conditions. For example, a speed-acceleration phase plot provides a general picture of the starting and stopping maneuvers made by the driver, of the level of accelerations and decelerations, and the character of the prevailing speeds. A great deal of important work remains to be carried out regarding driver behavior under real traffic conditions.

General Inferences

It is important to note that all of the theoretical ideas and models for car following, the kinetic theory of traffic, the two-fluid model, and the other approaches discussed here have been verified by various levels of experimentation and observation, as the reader can ascertain from the discussions in the various cited papers, and the references therein.

I believe that the message conveyed in these experiences with problems involving human behavior is that there is hope, contrary to much that has been said by researchers in general. Even though some problems are very complex and, moreover, even though human behavior may be one of the main driving forces, there is the hope, certainly in some instances, that it will prove possible to devise tractable models incorporating the influence of human behavior, and, through remarkable collective effects, perhaps have the good fortune to obtain relatively simple results. In my opinion, there is far too little reliance on data, the language of nature, in formulating models for the systems and processes of the deepest importance to human beings, namely, the problems in which we are actors. Our most important vision should be to simplify!

OTHER MATTERS

There are a number of vital questions of deep concern that I should like to share with you.

The Need for Vision in Traffic and Transportation Research

First, it is very important in my view to conduct research on traffic and transportation in the context of the overall infrastructure. I am aware of the effectiveness in science of focusing on narrow and well defined questions. However, I should like to encourage viewing these traffic problems from a global perspective. One of society's greatest concerns is the inexorable rise of traffic congestion in most of the large cities around the world. Cities are the summation and expression of the infrastructure, or more precisely, a set of infrastructures, working sometimes in harmony, sometimes with frustrating discord, to provide us with shelter, contact, energy, transportation, communication, water, and the means to meet various other human needs. The city is a symbol of what we are collectively, and its forms and functions sharpen our understanding of the differences among regions, groups and cultures. "The infrastructure is us." It is a reminder that we are what we were and will be what we are (Herman et al. 1988, Herman and Ausubel 1988).

It is for such philosophical reasons that we must view vehicular traffic and transportation in general in terms of their interaction with the rest of the infrastructure, particularly energy, communication, and the environment (Ausubel, Frosch and Herman 1989, Herman, Ardekani and Ausubel 1989). Society must be cognizant of what has been termed the paradox of technology, namely, that environmental disruption is brought about by the industrial economy, but that the advancement of the industrial economy has also been and will be the main route to environmental quality.

Moreover, attention should be given to the extraordinary regularity and universality of infrastructure development. A logistic substitution model can be used to organize the data on infrastructure systems for energy and transportation (Ausubel 1989). The model reveals long-wave pulses of growth arising from technological innovation that have periods of about 50 years and characterize the transformation of infrastructure. For example, the successive roles of the horse and automobile mesh with rather surprising precision, as do the life cycles of canals, railroads, roads, and air routes.

If we take a broad view of this discussion, it is apparent that there is a strong intertwining of a number of subject areas: vehicular traffic and its characteristics; control systems and strategies; pavement technology, construction and management; and geometric design. It is eminently clear that there would be no roads but for vehicles and drivers and little if any traffic but for the road system. Without rational design and effective control, such as would include in-vehicle information and guidance, we cannot expect to have a healthy and viable overall traffic system. Moreover, we require well engineered automobiles designed to take into account human characteristics; in addition, we expect reasonable human behavior with respect to a system of rational traffic laws and customs. Thus, we are dealing here with a classic example of a symplectic system—a *symplegma*!

Science and the Arts in Society

In science there is an entire spectrum of significant research activity ranging from formal and sometimes abstruse science to some of the most applied and practical efforts important on a day-to-day basis. I have always been greatly concerned with the importance of the flourishing of science and the arts for an overall healthy socioculture. I urge that we be sensitive at all levels to the proper support and funding of the kind of science that provides the very foundations for our socially vital subjects.

It is of the highest concern that we examine the state and future of the entire educational enterprise with special regard to nurturing the creative process. In addition, it is also crucial to consider the interaction of funding agencies with the university structure and the impact of the present style of funding research on scholarship in general and on the ability to perform creative research and teaching. There is much to be concerned about and, in my opinion, a considerably better state to aspire to. After all, the university is the principal institution in which it is possible for the best minds through creative teaching and creative research to provide the young with an exciting developmental experience by inspiring them to reach for knowledge and understanding as contrasted to the ever-growing, narrow prescriptive technical training of the information age.

In this context, let me touch on Thomas Jefferson's concern with social utility when the United States was very young (Martin 1952). In 1800 Jefferson drew up a rank ordering of the utility of the sciences for Joseph Priestley. This list was headed by botany and chemistry, with natural philosophy, mathematics, and astronomy in the middle of the list, and the fine arts at the end. Jefferson had an especially high regard for chemistry as one of the most useful sciences with great potential for future discoveries, and he expressed the opinion that agriculture was the most useful of the sciences for America. He qualified his recommendations regarding geology because he felt its conclusions were uncertain and it had no obvious utility, but he certainly showed a keen interest in mineral exploration. However, regarding the branch of knowledge which dealt with the formation and history of the earth he wrote,

> The dreams about the modes of creation, inquiries whether our globe has been formed by the agency of fire or water, how many millions of years it has cost Vulcan or Neptune to produce what the fiat of the Creator would effect by a simple act of will, is too idle to be worth a single hour of any man's life.

He went so far as to remark that it made little difference whether the earth is 600 or 6,000 years old.

I mention these thoughts because in Jefferson we have an example of a true Renaissance-type genius focusing on practical benefits for good reasons but with a somewhat less than open mind regarding the improbable fluctuations from which important knowledge may arise. Perhaps we can be sympathetic, since in those early days there were not sufficient resources and time to indulge in what might have appeared to be the luxury of theoretical speculation. However, at present we live in a mature sociotechnical culture and if we support only the works that appeal because we see useful end results, I believe that we must beware. Nobody is sufficiently prescient to fathom where important new developments may lie and we must avoid a lifestyle that smothers human receptivity to new thoughts and pathways.

It is extremely discouraging to read in a recent policy statement issued by one of our government agencies that all activities including research are to be conducted in a safe, reliable, and predictable manner. Brewster Ghiselin, an American poet, when discussing the creative process, said,

> It is essential to remember that the creative end is never in full sight at the beginning and that it is brought wholly into view only when the process of creation is completed. It is not to be found by scrutiny of the conscious scene, because it is never there (Ghiselin 1955).

It is regrettable that we have people at all levels in various agencies of government who control the support and funding of scientific and technological research in far too pragmatic a manner.

Another difficulty for the scientist or any creative artist has been expressed elegantly by Gertrude Stein:

> One does not ever understand, before they are completely created, what is happening and one does not at all understand what one has done until the moment when it is all done. Picasso said once that he who created a thing is forced to make it ugly. In the effort to create the intensity and the struggle to create this intensity, the result always produces a certain ugliness, those who follow can make of this thing a beautiful thing because they know what they are doing, the thing having already been invented, but the inventor because he does not know what he is going to invent inevitably the thing he makes must have its ugliness (Stein 1969).

We are all familiar with the intense scrutiny received by new ideas and results if they are disjoint with respect to present understanding and especially if they are perceived to be important. This is usually a healthy process, although some of the resistance to new ideas clearly comes from the conservative nature of the technical communities; and, of course, there is the not-invented-here syndrome.

I have always been keenly aware of the importance of the useful arts and have been highly pleased by whatever practical benefits have emanated from my own work. However, since there is at present an escalating tendency to move in pragmatic directions, I continue to make the plea that sponsoring organizations in our society act somewhat more in the role of enlightened patrons who support science, technology, and the arts to the greatest extent possible so that we continue to foster and nurture that most fragile and ephemeral creative boundary with the unknown that is so deeply and urgently required for human progress.

ORSA's Key Role

In these concluding remarks I would be remiss if I were not to mention that I strongly believe ORSA has a continuing important and key role to play in the future, since traditionally the Society has been concerned with modeling and solving complicated and complex problems involving human decision making. I urge the Society to continue to range further into the unknown and support creative and risky thinking, something rarely encouraged these days. I further suggest that our Society consider initiating some operations research studies of the entire educational enterprise and especially of the influence of funding methods on research and teaching in the university system in the spirit mentioned earlier in these remarks. As in the past, I continue to hope that we conduct our Society affairs to leave for future ORSA generations the sense that we have not only striven for excellence but also struggled with the unknown with integrity and foresight.

CONCLUSION

Some of what I have been trying to convey in this essay has been beautifully stated by Leonardo da Vinci, brilliant philosopher, scientist, engineer and musician, who left the following thoughts in his notebooks:

> Those who fall in love with practice without science are like a sailor who enters a ship without a compass and does not know whither he is going. . . . Science is the captain, practice the soldiers. . . . All sciences are vain and full of errors that have not been born by experience, mother of all certainty, and that are not tested by experience.

The eternal struggle for new knowledge that on the one hand adds to the inner core of our understanding and on the other has useful consequences for humanity requires a great and constant effort as well as a high level of devotion. This is, indeed, a most difficult creative task, made all the more so because as Heraclitus, the ancient Greek philosopher, said: "Nature seeks to hide."

We must remember that science is not an isolated pursuit; it is embedded in society itself and is connected to all knowledge and human experience. Science as we know it would not be possible if it were not for the deep conviction of all of us as individuals and of society as a whole that the pursuit of science is a great and uplifting endeavor, essential and relevant to both our material and spiritual evolution.

Finally, I should like to paraphrase an inspirational thought expressed by Socrates more than two millennia ago: We must rise above the Earth to the top of the atmosphere and beyond, for only then will we fully understand the world in which we live.

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