INTRODUCTION

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1. INTRODUCTION

It is hardly necessary to emphasize the importance of transportation in our lives. In the United States, we spend about 20 percent of Gross National Product (GNP) on transportation, of which about 85 percent is spent on highway transportation (passenger and freight). We own and operate 150 million automobiles and an additional 50 million trucks, bringing car ownership to 56 per hundred population (highest in the world). These vehicles are driven an average of 10,000 miles per year for passenger cars and 50,000 miles per year for trucks on a highway system that comprises more than 4 million miles. The indices in other countries may be somewhat different, but the importance of the transportation system, and especially the highway component of it, is just the same or even greater. While car ownership in some countries may be lower, the available highway network is also smaller leading to similar or more severe congestion problems.

Traffic flow theories seek to describe in a precise mathematical way the interactions between the vehicles and their operators (the *mobile* components) and the infrastructure (the *immobile* component). The latter consists of the highway system and all its operational elements: control devices, signage, markings, etc. As such, these theories are an indispensable construct for all models and tools that are being used in the design and operation of streets and highways. The scientific study of traffic flow had its beginnings in the 1930's with the application of probability theory to the description of road traffic (Adams 1936) and the pioneering studies conducted by Bruce D. Greenshields at the Yale Bureau of Highway Traffic; the study of models relating volume and speed (Greenshields 1935) and the investigation of performance of traffic at intersections (Greenshields 1947). After WWII, with the tremendous increase in use of automobiles and the expansion of the highway system, there was also a surge in the study of traffic characteristics and the development of traffic flow theories. The 1950's saw theoretical developments based on a variety of approaches, such as car-following, traffic wave theory (hydrodynamic analogy) and queuing theory. Some of the seminal works of that period include the works by Reuschel (1950a; 1950b; 1950c), Wardrop (1952), Pipes (1953), Lighthill and Whitham (1955), Newell (1955), Webster (1957), Edie and Foote (1958), Chandler et al. (1958) and other papers by Herman et al. (see Herman 1992).

By 1959 traffic flow theory had developed to the point where it appeared desirable to hold an international symposium. The First International Symposium on The Theory of Traffic Flow was held at the General Motors Research Laboratories in Warren, Michigan in December 1959 (Herman 1961). This was the first of what has become a series of triennial symposia on The Theory of Traffic flow and Transportation. The most recent in this series, the 12th symposium was held in Berkeley, California in 1993 (Daganzo 1993). A glance through the proceedings of these symposia will provide the reader with a good indication of the tremendous developments in the understanding and the treatment of traffic flow processes in the past 40 years. Since that time numerous other symposia and specialty conferences are being held on a regular basis dealing with a variety of traffic related topics. The field of traffic flow theory and transportation has become too diffuse to be covered by any single type of meeting. Yet, the fundamentals of traffic flow theory, while better understood and more easily characterized through advanced computation technology, are just as important today as they were in the early days. They form the foundation for all the theories, techniques and procedures that are being applied in the design, operation, and development of advanced transportation systems.

It is the objective of this monograph to provide an updated survey of the most important models and theories that characterize the flow of highway traffic in its many facets. This monograph follows in the tracks of two previous works that were sponsored by the Committee on Theory of Traffic Flow of the Transportation Research Board (TRB) and its predecessor the Highway Research Board (HRB). The first monograph, which was published as HRB Special Report 79 in 1964, consisted of selected chapters in the then fledgling Traffic Science each of which was written by a different author (Gerlough and Capelle 1964). The contents included:

Chapter 1. Part I: Hydrodynamic Approaches, by L. A. Pipes. Part II: On Kinematic Waves; A Theory of Traffic Flow on Long Crowded Roads, by M. J. Lighthill and G. B. Whitham.

Chapter 2. Car Following and Acceleration Noise, by E. W. Montroll and R. B. Potts.

Chapter 3. Queuing Theory Approaches, by D. E. Cleveland and D. G. Capelle.

Chapter 4. Simulation of Traffic Flow, by D. L. Gerlough.

Chapter 5. Some Experiments and Applications, by R. S. Foote.

A complete rewriting of the monograph was done by Gerlough and Huber (1975) and was published as TRB Special Report 165 in 1975. It consisted of nine chapters, as follows:

Chapter 1. Introduction.

Chapter 2. Measurement of Flow, Speed, and Concentration.

Chapter 3. Statistical Distributions of Traffic Characteristics.

Chapter 4. Traffic Stream Models.

Chapter 5. Driver Information Processing Characteristics.

Chapter 6. Car Following and Acceleration Noise.

Chapter 7. Hydrodynamic and Kinematic Models of Traffic.

Chapter 8. Queuing Models (including Delays at Intersections).

Chapter 9. Simulation of Traffic Flow.

This volume is now out of print and in 1987 the TRB Committee on Traffic Flow Theory and Characteristics recommended that a new monograph be prepared as a joint effort of committee members and other authors. While many of the basic theories may not have changed much, it was felt that there were significant developments to merit writing of a new version of the monograph. The committee prepared a new outline which formed the basis for this monograph. After the outline was agreed upon, the Federal Highway Administration supported this effort through an interagency agreement with the Oak Ridge National Laboratory. An Editorial Committee was appointed, consisting of N. H. Gartner, C. J. Messer, and A. K. Rathi, which was charged with the editorial duties of the preparation of the manuscripts for the different chapters.

The first five chapters follow similarly titled chapters in the previous monograph; however, they all have been rewritten in their entirety and include the latest research and information in their respective areas. Chapter 2 presents the various models that have been developed to characterize the relationships among the traffic stream variables: speed, flow, and concentration. Most of the relationships are concerned with uninterrupted traffic flow, primarily on freeways or expressways. The chapter stresses the link between theory and measurement capability, since to as large extent development of the first depends on the latter.

Chapter 3, on Human Factors, discusses salient performance aspects of the human element in the context of the person-machine system, i.e. the motor vehicle. The chapter describes first discrete components of performance, including: perception-reaction time, control movement time, responses to traffic control devices, to the movement of other vehicles, to hazards in the roadway, and how different segments of the population differ in performance. Next, the kind of control performance that underlies steering, braking, and speed control -- the primary control functions -- is described. Applications of open-loop and closed-loop vehicle control to specific maneuvers such as lane keeping, car following, overtaking, gap acceptance, lane closures, and sight distances are also described. To round out the chapter, a few other performance aspects of the driver-vehicle system are covered, such as speed limit changes, distractions on the highway, and responses to real-time driver information. The most obvious application of human factors is in the development of Car Following Models (Chapter 4). Car following models examine the manner in which individual vehicles (and their drivers) follow one another. In general, they are developed from a stimulus-response relationship, where the response of successive drivers in the traffic stream is to accelerate or decelerate in proportion to the magnitude of the stimulus at time t after a time lag T. Car following models form a bridge between the microscopic behavior of individual vehicles and the macroscopic characteristics of a single-lane traffic stream with its corresponding flow and stability properties.

Chapter 5 deals with Continuous Flow Models. Because traffic involves flows, concentrations, and speeds, there is a natural tendency to attempt to describe traffic in terms of fluid behavior. Car following models recognize that traffic is made up of discrete particles and it is the interactions between these particles that have been developed for fluids (i.e., continuum models) is concerned more with the over all statistical behavior of the traffic stream rather than with the interactions between the particles. In the fluid flow analogy, the traffic stream is treated as a one dimensional compressible fluid. This leads to two basic assumptions: (i) traffic flow is conserved, which leads to the conservation or continuity equation, and (ii) there is a one-to-one relationship between speed and density or between flow and density. The simple continuum model consists of the conservation equation and the equation of state (speed-density or flow-density relationship). If these equations are solved together with the basic traffic flow equation (flow equals density times speed) we can obtain the speed, flow and density at any time and point of the roadway. By knowing these basic traffic flow variables, we know the state of the traffic system and can derive measures of effectiveness, such as delays, stops, travel time, total travel and other measures that allow the analysts to evaluate how well the traffic system is performing. In this chapter, both simple and high order models are presented along with analytical and numerical methods for their implementation.

Chapter 6, on Macroscopic Flow Models, discards the microscopic view of traffic in terms of individual vehicles or individual system components (such as links or intersections) and adopts instead a macroscopic view of traffic in a network. A variety of models are presented together with empirical evidence of their applicability. Variables that are being considered, for example, include the traffic intensity (the distance travelled per unit area), the road density (the length or area of roads per unit area of city), and the weighted space mean speed. The development of such models extends traffic flow theory into the network level and can provide traffic engineers with the means to evaluate system-wide control strategies in urban areas. Furthermore, the quality of service provided to motorists can be monitored to assess the city's ability to manage growth. Network performance models could also be used to compare traffic conditions among different cities in order to determine the allocation of resources for transportation system improvements. Chapter 7 addresses Traffic Impact Models, specifically, the following models are being discussed: Traffic and Safety, Fuel Consumption Models, and Air Quality Models.

Chapter 8 is on Unsignalized Intersection Theory. Unsignalized intersections give no positive indication or control to the driver. The driver alone must decide when it is safe to enter the intersection, typically, he looks for a safe opportunity or "gap" in the conflicting traffic. This model of driver behavior is called "gap acceptance." At unsignalized intersections the driver must also respect the priority of other drivers. This chapter discusses in detail the gap acceptance theory and the headway distributions used in gap acceptance calculations. It also discusses the intersections among two or more streams and provides calculations of capacities and quality of traffic operations based on queuing modeling.

Traffic Flow at Signalized Intersections is discussed in Chapter 9. The statistical theory of traffic flow is presented, in order to provide estimates of delays and queues at isolated intersections, including the effect of upstream traffic signals. This leads to the discussion of traffic bunching, dispersion and coordination at traffic signals. The fluid (shock-wave) approach to traffic signal analysis is not covered in this chapter; it is treated to some extent in Chapter 5. Both pretimed and actuated signal control theory are presented in some detail. Further, delay models that are founded on steady-state queue theory as well as those using the so-called coordinate transform method are covered. Adaptive signal control is discussed only in a qualitative manner since this topic pertains primarily to the development of optimal signal control strategies, which is outside the scope of this chapter.

The last chapter, Chapter 10, is on Traffic Simulation. Simulation modeling is an increasingly popular and effective tool for analyzing a wide variety of dynamical problems which are not amenable to study by other means. These problems are usually associated with complex processes which can not readily be described in analytical terms. To provide an adequate test bed, the simulation model must reflect with fidelity the actual traffic flow process. This chapter describes the traffic models that are embedded in simulation packages and the procedures that are being used for conducting simulation experiments.

Consideration was also given to the addition of a new chapter on Traffic Assignment Models. Traffic assignment is the process of predicting how a given set of origin-destination (OD) trip demands will manifest themselves onto a transportation network of links and nodes in terms of flows and queues. It has major applications in both transportation planning models and in dynamic traffic management models which are the bedrock of Intelligent Transportation Systems (ITS). Generally, the assignment process consists of a macroscopic simulation of the behavior of travelers in a network of transportation facilities. At the same time it reflects the interconnection between the microscopic models of traffic behavior that are discussed in this monograph and the overall distribution of traffic demands throughout the network. This is expressed by link cost functions that serve as a basis for any assignment or route choice process. After much deliberation by the editorial and advisory committees it was decided that the subject cannot be presented adequately in a short chapter within this monograph. It would be better served by a dedicated monograph of its own, or by reference to the extensive literature in this area. Early references include the seminal works of Wardrop (1952), and Beckmann, McGuire and Winsten (1956). Later publications include books by Potts and Oliver (1972), Florian (1976), Newell (1980), and Sheffi (1985). Recent publications, which reflect modern approaches to equilibrium assignment and to dynamic traffic assignment, include books by Patriksson (1994), Ran and Boyce (1994), Gartner and Improta (1995), Florian and Hearn (1995), and Bell and Iida (1997). This is a lively research area and new publications abound.

Research and developments in transportation systems and, concomitantly, in the theories that accompany them proceed at a furious pace. Undoubtedly, by the time this monograph is printed, distributed, and read, numerous new developments will have occurred. Nevertheless, the fundamental theories will not have changed and we trust that this work will provide a useful source of information for both newcomers to the field and experienced workers.

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