TRAFFIC AND GRANULAR FLOW '07

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With 397 Figures, 197 in Colour, and 29 Tables

Springer

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ISBN 978-3-540-77073-2 e-ISBN 978-3-540-77074-9

DOI 10.1007/978-3-540-77074-9

Library of Congress Control Number: 2008944305

Mathematics Subject Classification (2000): 90B20, 90B06, 90B15, 90B18, 60K30, 76T25, 65C20, 65C35, 68U20, 92C05, 92D50, 60K20

Cover design: WMXDesign GmbH, Heidelberg

Printed on acid-free paper

9 8 7 6 5 4 3 2 1

springer.com

Preface

The "Traffic and Granular Flow '07" conference was the seventh of a series of international conferences that started in 1995 in Jülich (Germany). Since then, the conference took place in Duisburg (1997), Stuttgart (1999), Nagoya (2001), Delft (2003) and Berlin (2005).

The aim of TGF conferences is to facilitate the exchanges between various fields dealing with transport. When the conference was created, the fields that were represented were road traffic and granular flow – hence the name of the series. Since then, the scope of the conference has been enlarged to include in particular collective motion in biology (molecular motors), a subject which turns out to have many connections with the two original ones.

Transversal themes have emerged. For TGF07, a session was specifically devoted to the subject of networks. An important theme is also the one of self-propelled particles. It ranges from granular flows with anisotropic grains, to collective motion of animals, and to pedestrian traffic.

We were very happy to organize the 2007 occurrence of TGF in Orsay (France), at the University Paris-Sud. The conference was organized mainly by the Laboratory of Theoretical Physics (LPT), with the help of the Laboratory FAST (Fluides, Automatique et Systèmes Thermiques) – these two laboratories are both associated to the CNRS (Centre National pour la Recherche Scientifique) – and of the GARIG Group at INRETS.

With more than 2000 researchers or teaching researchers, University Paris-Sud represents 4% of the french public research. More than 25000 students are studying at this university. It is known for its high scientific level. Recently, the Fields medal (2006) honored Wendelin Werner, professor at the mathematical departement at the Orsay campus. In 2007, the physics Nobel price was given to A. Fert, professor at University Paris-Sud.

Besides, the Orsay campus is located in a scientifically very active area, very near for example Ecole Polytechnique and CEA.

In France, research on road traffic is mainly performed in specialized public research centers, the main two being INRETS (Institut National de Recherche sur les Transports et leur Sécurité) and LCPC (Laboratoire Central des Ponts et Chaussées). Both of them have important research centers in region Ile-de-France. Besides, for the sake of building roads, LCPC also has an active research activity in the granular field.

The TGF07 conference was the opportunity to gather national actors as well as international researchers. It took place from the 20th to 22nd of June 2007. 127 participants from 24 nationalities were present. The 8 plenary talks and the 70 posters allowed exchanges between the various communities. Parallel sessions (48 oral presentations) allowed more specialized and thorough discussions within each field.

We would like to thank our sponsors. We are especially grateful to Region Ile-de-France, first because it was our main sponsor, but also because it was the only one who gave us an answer enough in advance, so that we could decide to go on. Without Region Ile-de-France, this conference would not have taken place. The conference was supported also by the CEA (Commissariat à l'énergie atomique), the ministry of research, the RTRA "triangle de la physique", CNRS, INRETS, DGA, University Paris-Sud, the French embassy in India, and the European Physical Journal.

We would like to thank Olivier Dauchot and Cécile Sykes for their valuable help on scientific and pratical issues, and Henk Hilhorst, the director of the Laboratory of Theoretical Physics, for his support during the preparation of the conference. Odile Heckenauer and Mireille Calvet deserve a special thank-you for all the administrative and organizational work they did before the conference, and for their presence during the whole conference at the welcome desk. Thank-you also to Gérard Hoffeurt, Manuel Ramos, Antoine Seguin and Yann Bertho for their help before and during the conference. We are grateful to Mrs. Dahm-Courths for the great work she did on the proceedings.

Paris, Duisburg
October 2008

Cécile Appert-Rolland
François Chevoir
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Avant-Propos

La conférence internationale “Traffic and Granular Flow ’07” (TGF07) était la 7ème d’une série qui a débuté en 1995 à Jülich (Allemagne). Depuis, des conférences TGF ont eu lieu à Duisburg (1997), Stuttgart (1999), Nagoya (2001), Delft (2003) et Berlin (2005).

L’objectif des conférences TGF est de faciliter les interactions entre divers domaines de recherche touchant au transport. Lors de la création de cette série de conférences, les domaines représentés étaient le trafic routier et les écoulements granulaires – d’où le nom de la série. Depuis, les thèmes abordés se sont multipliés, en particulier pour inclure les mouvements collectifs en biologie (moteurs moléculaires), un sujet qui s’est avéré avoir des problématiques communes avec les thèmes d’origine de la conférence.

Des thèmes plus transversaux émergent peu à peu. Lors de TGF07, une session a été spécialement consacrée aux réseaux. Un autre thème important est celui des particules auto-propulsées, qui va des écoulements granulaires à grains anisotropes aux mouvements collectifs d’animaux, et au trafic piéton.

Nous étions très heureux de pouvoir organiser TGF07 à Orsay (France), à l’Université Paris-Sud. La conférence a été essentiellement organisée par le Laboratoire de Physique Théorique (LPT), avec l’aide du Laboratoire FAST (Fluides, Automatique et Systèmes Thermiques) – ces deux laboratoires sont tous deux associés au CNRS (Centre National pour la Recherche Scientifique) – et du groupe GARIG à l’INRETS.

Avec plus de 2000 chercheurs ou enseignants-chercheurs, l’Université Paris-Sud représente 4% de la recherche publique française. Plus de 25000 étudiants y étudient. L’Université Paris-Sud est reconnue pour son haut niveau scientifique. Récemment, la médaille Fields (2006) a été remise à Wendelin Werner, professeur au Département de Mathématiques du campus d’Orsay. En 2007, le prix Nobel de physique a été décerné à A. Fert, professeur à l’Université Paris-Sud.

Le campus d’Orsay est de plus situé dans un environnement scientifique très actif, proche par exemple de l’ Ecole Polytechnique et du CEA.

En France, la recherche sur le trafic routier est principalement effectuée dans des centres de recherche publique spécialisés, les deux principaux étant l'INRETS (Institut National de Recherche sur les Transports et leur Sécurité) et le LCPC (Laboratoire Central des Ponts et Chaussées). Tous les deux ont d'importants centres de recherche en région Ile-de-France. De plus, le LCPC a aussi une grosse activité de recherche sur les milieux granulaires, liée à la fabrication et à l'entretien des infrastructures (routes ...).

La conférence TGF07 a été l'occasion de réunir acteurs nationaux et chercheurs étrangers. Elle a eu lieu du 20 au 22 Juin 2007. 127 participants de 24 nationalités différentes étaient présents. Les 8 sessions plénières et les 70 posters ont permis de nombreux échanges entre les diverses communautés, tandis que les sessions parallèles (communications orales) ont été le lieu de discussions plus spécialisées et plus approfondies au sein de chaque sujet.

Nous souhaitons maintenant remercier nos sponsors. Nous sommes tout spécialement reconnaissants envers la région Ile-de-France, d'une part parce que c'était notre sponsor principal, mais aussi parce que c'était le seul qui nous ait donné une réponse suffisamment à l'avance pour que nous puissions décider de nous lancer dans l'organisation de cette conférence. Sans la région Ile-de-France, cette conférence n'aurait pas eu lieu. La conférence TGF07 a aussi été soutenue financièrement par le CEA (Commissariat à l'énergie atomique), le ministère de la recherche, le RTRA "triangle de la physique", le CNRS, l'INRETS, la DGA, l'Université Paris-Sud, l'ambassade de France en Inde, et le European Physical Journal.

Nous aimerions remercier ici Olivier Dauchot et Cécile Sykes pour leur aide précieuse tant sur le plan scientifique que pratique, et Henk Hilhorst, directeur du Laboratoire de Physique Théorique, pour son soutien tout au long de la préparation de la conférence. Nous devons des remerciements tout particuliers à Odile Heckenauer et Mireille Calvet pour tout leur travail administratif et d'organisation avant la conférence, et pour leur présence pendant toute la conférence à la table d'enregistrement. Merci aussi à Gérard Hoffeurt, Manuel Ramos, Antoine Seguin et Yann Bertho pour leur aide avant et pendant la conférence. Nous sommes reconnaissants envers Mme Dahm-Courths pour le travail effectué pour les Actes de la conférence.

Paris, Duisburg
Octobre 2008

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Part I

Traffic

Modelling of Traffic Flow from an Engineer's Perspective

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1 Introduction

The purpose of this short paper is threefold. First, it highlights the requirements of a traffic engineer from a model of traffic flow; that is, it discusses what properties of a flow model will make it attractive and useful to an engineer. Second, the paper points out the basic features of the existing models of traffic flow. Third, the paper presents some of the work done by the authors to develop models which attempt to meet some of the needs of traffic engineers.

The paper is divided into five sections of which this is the first. The second, third and fourth sections are devoted to the three points mentioned in the previous paragraph. The last section summarizes this paper.

2 An Engineer's Requirements from Traffic Flow Models

A traffic engineer is entrusted with the duty of designing and efficiently operating facilities which aid in the mobility of goods and vehicles. This task is the most challenging when it comes to road traffic for a variety of reasons: (i) there are a large number of vehicles on roads, (ii) these vehicles belong to different classes with widely varying operating characteristics, and (iii) each vehicle is driven by a human driver whose nature and characteristics vary. In physical terms, traffic engineers dealing with road traffic essentially deal with a system which has a large number of particles of various shapes and sizes, whose response to different situations are different and are "motivated." In addition to introducing the issue of "motive," the involvement of human drivers in the system cause roadway and traffic features to have psychological (in addition to physical) impact on the stream behaviour.

Roadway features include various aspects of the road like road width, shoulder width, grade (or slope), curves — their frequency and curvature, surface conditions, etc. Traffic features include, the vehicle mix in the stream, the driver mix in the stream, traffic rules (like speed limit) and other control measures (like signals, signs, etc.). Based on how these different aspects are present in a situation (or facility), a traffic engineer often divides the flow into two broad categories: uninterrupted flow and interrupted flow. The former relates to flow seen on freeways and expressways while the latter relates to flow seen on arterials and other urban streets. In the former type, the traffic stream primarily gets impacted by the roadway features and some traffic rules but unlike in the interrupted stream case does not go through intersections with conflicting movements. For instance, the Highway Capacity Manual defines uninterrupted flow as flow (or stream) that "results from the interactions among vehicles in the stream and between vehicles and the geometric and environmental characteristics of the roadway;" while interrupted flow is the flow on facilities which have elements (like traffic signal, stop signs) which stop traffic periodically irrespective of the flow or traffic that exists [1].

In this paper the discussion concentrates on uninterrupted traffic flow and what are required of models of such flows. The reason for concentrating on uninterrupted traffic flow is that a large part of a nation's road network (for example the expressway system) as well as some sections of arterials (with large inter-intersection separation) and rural roads carry traffic which are largely uninterrupted. To begin the discussion, first, the way in which an engineer views a transport facility catering to uninterrupted traffic flow is described. For an engineer, a facility catering to uninterrupted flow is a system characterized by a set of parameters which the engineer can control; for example, the lane width and the number of lanes, the shoulder width, the grades on the road, the types and frequency of horizontal curves on the road, etc. What is of paramount importance to the engineer is to know what impact changes in these parameters will have on the ability of the facility to provide efficient transportation. More specifically, one is interested in knowing, for a given combination of the various design parameters, what will be the average speed, density of the stream at various flow levels (or loosely speaking, demand levels), what is the maximum value of flow (or capacity) that can be handled by the facility, what kind of level of service the road will provide to its users, how sensitive will travel time on the road be to minor changes in demand levels, and many more such questions.

Stated differently, the speed-flow, (or flow-density or speed-density) relation of a road and how this relation depends on the various parameters outlined above is of interest to a traffic engineer. These relations, in a way, give the engineer a sense of how a design will respond to various demand levels. Thus the engineer needs a model of traffic flow (or uninterrupted traffic flow) which will be able to provide, at the very basic, the relationship between speed and flow for heterogeneous streams (both with respect to vehicles and drivers) going through roads of varying characteristics (geometry). In addition to the points mentioned here, an engineer would also expect the uninterrupted traffic flow models to (i) predict the impact of incidents on the traffic flow, (ii) understand the perturbations that occur when streams merge or diverge (like at an on or off ramp); and (iii) incorporate lane changing whenever lane discipline is present. It must be mentioned that there exists streams where lane discipline is absent; for example traffic on Indian expressways hardly ever move along lanes. One needs to model traffic for such roads also for the same reasons as above.

Enhancing the need for such models is the fact that a traffic engineer does not have a laboratory where he/she can perform controlled experiments or what-if studies; for example, one will not be able to "see" what might happen if an extra curve is introduced on the road or if an obstacle is placed on the road. This increases a traffic engineer's reliance on models of traffic flow which can simulate traffic realistically under a variety of conditions.

3 Uninterrupted Traffic Flow and its Models

In this section, uninterrupted flow and certain parameters which help quantify the flow are discussed. Next, the existing classes of models for such uninterrupted flow are briefly described. This description is excerpted from a previous paper by the author [2].

3.1 Uninterrupted Traffic Streams

In the previous section a small description was provided on what is meant by uninterrupted flow and why it is important to study such flow. In this section uninterrupted flow and its characteristics are looked at in slightly greater detail.

An uninterrupted traffic stream is an outcome of the responses of individual drivers to the immediate driving scenario. The responses of drivers are in terms steering and speed control. These controls are achieved through a sequence of steering angle and acceleration rate choices. Three different interactions cause a particular flow to occur; these are driver-vehicle interactions, vehicle-vehicle interactions, vehicle-road interactions. These are briefly described in the following paragraphs.

A vehicle has certain operating characteristics and these characteristics impact how a driver interacts with the vehicle he/she is driving which in turn shows up in the behaviour of a driver-vehicle pair. For example, drivers driving two-wheelers often react differently to a situation than say a driver driving an eighteen-wheeler because the former has greater acceleration capabilities, respond faster to driver actions, and has higher maneuverability. This variation has implications on stream behaviour when a stream has a mix of vehicles with widely varying operating characteristics.

When lane discipline is present, vehicles typically interact with the vehicle ahead in the same lane while driving. Observations tend to suggest that the following vehicle (FV) reacts to the relative speed and distance headway between itself and the leading vehicle. The reaction is often impacted by the speed at which the FV is travelling. This phenomenon is called car-following and has been studied extensively. The next section briefly describes some of the existing models of car-following. Vehicles also interact with other vehicles in the vicinity when passing or changing lanes. In cultures where lane discipline is weak the vehicle-vehicle interaction is far more complex than when lane discipline is present. In such situations vehicles interact with a host of vehicles in its vicinity and a clear lead vehicle does not exist. That is, there is both longitudinal and lateral interaction between vehicles. Recent work (see Gunay [3]) also suggests that even when lane discipline is present vehicles other than the one directly ahead have an impact on how a vehicle moves. From a theoretical perspective, the two situations are qualitatively different; when lateral interactions are absent the flow is an outcome of unidimensional (or linear) interaction between vehicles, whereas when lateral interactions are present the flow is an outcome of two-dimensional interaction between vehicles. The next section presents some models which attempt to incorporate the two-dimensional interaction between vehicles.

Static features of the road like road (or lane) width, horizontal curves, surface deformities, etc. also impact the vehicle (driver) behaviour. Observations suggest that the nature of the speed-flow relations (or alternatively speed-density relations) change with various geometric features of the road [1]. The impact of surface deformities (like large potholes) or obstacles (like an out-of-order vehicle) can cause large disruptions to traffic flow. For example, as per HCM 2000 [4] estimates, if an obstacle causes a lane blockage on a three lane expressway, then capacity of the road falls by 50% (notice that it is much greater than 33%). The interesting aspect of a vehicle-road interaction is that often (or for large parts) the interaction is due to lateral "forces" since there is generally no binding on ones forward motion (except when obstacles occupy the carriageway); for example drivers drive more carefully (i.e., maintain larger distances at lower speeds than they would normally do) on narrow roads because they feel constrained by the closeness of the road edges from the lateral directions. The reason for bringing this up here is to highlight the fact that if one attempts to develop models which incorporate vehicle-road interactions then such models must be able to handle lateral interactions.

Uninterrupted flow has certain defining characteristics; some are microscopic in nature while others are macroscopic. In the following some of the important microscopic and macroscopic characteristics of uninterrupted traffic streams are mentioned and the reader is directed to certain sources which present these characteristics in greater detail.

Microscopic Features

1. Drivers in uninterrupted streams at reasonable flow levels, for the most parts, follow the vehicle ahead and is impacted by the actions of that vehicle. The behaviour exhibited by drivers in such situations is referred to as car-following behaviour and has been studies extensively. Car-following behaviour has certain characteristics properties like, local and asymptotic

stability, closing-in and shying-away, etc. One may refer to May [5] or Chakroborty and Kikuchi [6] for a detailed description of the properties of car-following behaviour.

2. Acceleration noise is the root mean square deviation of acceleration of a vehicle over a period of time (see Herman et al. [7], Jones and Potts [8]) and is a parameter which can characterize the behaviour of a driver in a given driving environment. Winzer [9] did a detailed study on acceleration noise observed in real traffic streams at various flow conditions. Among other things, he found that average acceleration noise of vehicles tend to rise with density before reducing again; typically acceleration noise is below 0.6 m/s^2, etc.
3. The time headway distributions of uninterrupted streams have certain distinguishing features. At low flows, the distribution closely resembles a shifted exponential distribution (i.e., the vehicle arrivals are Poisson like); as flow increases the distribution gets right skewed and can be described reasonably well through Gamma distributions. The mode of the distribution is generally less than the median which is less than the mean; typically the mean is around the 67-percentile value. Further, the ratio of standard deviation of time headway to its mean generally approaches 1 from below as flow increases. The interested reader may refer to May [5] for more details on time headway distributions.
4. Speed distributions are typically symmetric with the mean value reducing with flow in the free flow region. Another interesting feature of such streams is that average speed varies transversely across the stream; it is highest on the median lane (left most lane on roads with keep-right policy) and lowest on the shoulder lane. One may refer to May [5] or Kang and Chang [10] for more details.

Macroscopic Features

1. Relationships exist between the three basic parameters of traffic streams, namely, flow, speed and density (or occupancy). Given the fundamental relation of traffic flow (see Equation 1 provided later), issues of data collection, and the engineering requirements, often speed-flow relationships are the only relations that are looked at. A large amount of empirical work has been done to study these relations (for example, see Hall [11], Hall et al. [12], Banks [13]) and the basic points that emerge are: (i) there are three distinct regimes, namely, uncongested, queue discharge, and congested regimes, (ii) the general shape can be approximated as that shown in Figure 1, (iii) the speed remains more or less constant till about 75% of the maximum flow, (iv) there seems to be a drop in the maximum flow value along the different arms of the relationship (see Figure 1); this value, though difficult to observe, has been estimated to be around 3 to 5% of the pre-congestion maximum flow (see Banks [14, 15] and Agyemang-Duah and Hall [16]), (v) the location of the arm corresponding to the

congested regime is often very difficult to fix and some even doubt the credibility of having such a precise relation in this region (see Ross [17]). Before leaving this point, it may be mentioned that, often streams do not operate at "equilibrium" and hence the observations on speed and flow at a given time may not indicate the equilibrium state of the system.

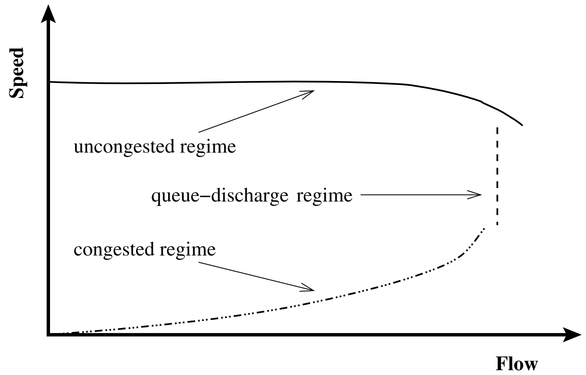

Fig. 1. Schematic showing the understanding of the shape of speed-flow relationships.

2. Geometry affects the dynamics of a traffic stream because of the impact it has on drivers. The shape and nature of the relationships between stream parameters change with changing geometry. Geometric features like lane (or road) width, lateral clearance (or shoulder width), grades, curves, etc. affect the speed-flow (and all other) relations. One may refer to HCM [1], or any other text book on transportation for more discussion on this.
3. Vehicles of different types have different impact on the stream behaviour due to differences in operating characteristics. Often these impacts are large; for example, the maximum flow rate (in vehicles per hour) on a plain terrain road may be reduced by a third if all the vehicles are trucks and not passenger cars. As can be imagined, different types of drivers have different impacts on the stream behaviour also. The reader may refer to HCM [1] for an idea as to how these impacts are taken into account in engineering studies with traffic streams.

In this section, some microscopic and macroscopic characteristics of an uninterrupted traffic stream are highlighted. It is felt that realistic models of traffic flow should strive to achieve these properties. A microscopic model of traffic flow — that is, one which models traffic flow by modelling individual vehicle motion, must show the microscopic as well as macroscopic properties of traffic streams (some of which are highlighted here).

3.2 Existing Models

The aim of this section is to look at some of the models of traffic flow, in general, and to point out, from an engineer's standpoint, those areas which need improvement. Consequently, this section is not to be treated as an exhaustive review of the various models developed in traffic flow. The models are presented under two classes, namely macroscopic models and microscopic models. The macroscopic models describe traffic flow in terms of average stream parameters while the microscopic models try to capture stream behaviour by describing individual vehicle motion. The microscopic models, at least in theory, can be used to study macroscopic properties of traffic streams.

Macroscopic Models

Macroscopic models of uninterrupted traffic streams typically include the fundamental relation (see Equation 1), the continuity equation (see Equation 2) and some relationship reflecting driver behaviour. Over the years, different models have been proposed for this relationship. In a latter paragraph brief descriptions of these models are provided. First, the fundamental and continuity equations are presented; in the equations, q is the flow, k is the density, u is the speed of the stream, x is the distance and t is time.

$$q = uk \tag{1}$$

$$\frac{\partial q}{\partial x} + \frac{\partial k}{\partial t} = 0 \tag{2}$$

Driver behaviour is often defined through a relation between u and k. Although, other pair wise relations (like $u - q$, $q - k$ relations) are often reported and studied, it is felt that, while describing driver behaviour, $u - k$ relations are the most fundamental as they are a direct outcome of the driving process (note that it is difficult to imagine that individual drivers have any notion of q while driving).

Over the years various models on u-k relations have been suggested. In the thirties, Greenshields [18] proposed a linear relation; later Greenberg [19] proposed a logarithmic relation based on fluid flow analogies of traffic stream movement. One of the most general descriptions of the u-k relation is the generalized polynomial model derived from microscopic models of driver behaviour (see May [5] for more details). This model is given in Equation 3; where, u_f and k_j are free flow speed and jam density, respectively and m and ℓ are calibration constants.

$$u^{1-m} = u_f^{1-m} \left[1 - \frac{k}{k_j} \right]^{\ell - 1} \tag{3}$$

Many researchers have raised objections to the use of a single function to describe the u-k relation over the entire density range (the so-called single regime models) on the grounds that humans do not behave according to the same rules over the entire range of density values. There is some merit to these objections. Many multi-regime models were proposed with Edie's [20] model being one of the first. Yet other researchers argued that it is better to look at the relationship among all the three parameters at once (for example see Navin [21], and Persaud and Hall [22]).

Unfortunately, there has been very little work on developing a model which describes the impact of geometry and other road features on driver behaviour. The Highway Capacity Manual [1], however, makes an attempt to relate geometric and other conditions to the speed-flow relation through a procedure which uses various empirically derived look-up tables to determine what the free flow speed will be in a given situation and then uses this free speed to choose an appropriate speed-flow curve from a template. In spite of such attempts, the fact remains that one does not have a model which given the geometric conditions will be able to determine the nature of the driver behaviour.

It must be pointed out here, at the cost of being repetitive, that a lot of research is going on in trying to replicate the observed macroscopic relations from simple driving rules; however, little or no research is currently on to relate roadway features and traffic features (like vehicle mix, driver mix, etc.) to the flow behaviour. Hence, reliance of traffic engineers on ad hoc procedures, to relate these aspects, continues. Despite advances in computation abilities and theoretical insight this reliance has not changed in the last half-a-century. Surely, this needs to change and the author feels researchers must now channelize their energy to evolve models which will reduce such reliance.

Microscopic Models

As opposed to the macroscopic models, microscopic models attempt to define the behaviour of a traffic stream by describing the behaviour of individual drivers in different driving situations. In general, drivers have two basic tasks, (i) controlling the vehicle's position along the direction of motion, and (ii) controlling the vehicle's position along the width of the road or lane. The first task is referred to as longitudinal control and is achieved by controlling the vehicle's speed (through acceleration / deceleration). The second task of lateral control is achieved through proper choice of steering angles. In reality both these activities are inter-dependent and goes on concurrently.

However, in order to simplify the understanding of driving behaviour, often it is assumed that the primary task of a driver is the longitudinal control of the vehicle. This assumption is largely true where the road characteristics are reasonably same for long distances, vehicles have well demarcated travel paths (like lanes) and vehicles do not generally cross these demarcations; even when they do it is a discrete event (like lane changing). Under these assumptions, the vehicle is assumed to be only under the influence of vehicles traveling in the same path (or lane); that is, only longitudinal interactions are taken into account. In the following, some of the properties of longitudinal control behaviour and its models are described.

The driver's behaviour in situations where the driver primarily performs longitudinal control can be broadly divided into three regimes: (i) free flow behaviour, (ii) car-following behaviour, and (iii) stop-and-go behaviour.

In free flow behaviour the driver is not encumbered by other drivers. The driver can choose his speed and maintain it purely at will. No models, except ones which can determine the choice of speeds (or free speeds) of vehicles given the road conditions are necessary. These are not within the purview of longitudinal control models, rather such choice of speeds are affected by the lateral impact of roads edges and other such static obstacles on the driver's mind. Further, free flow behaviour occurs when density is very low and the average distance headway between vehicles is much larger than what can be reasonably assumed to be a value at which leading vehicles (LVs) can hinder the following vehicle's (FV's) motion.

As densities increase vehicles start traveling closer to one another. In such situations the actions of a vehicle are affected by the state (or actions) of the LV; speeds of vehicles fall below their desired speed and there is constant tug-o-war between two conflicting motivators — the need to reach the destination as quickly as possible (i.e., urgency) and the concern for ones safety. Further, it is human nature to feel threatened if distance headway is small at high speeds; hence as distances reduce so does speed (this can be seen on a macroscopic scale from any data on u and k). So what happens is that the following vehicle constantly tries to increase the speed (effect of urgency) but in so doing closes in; this increases the threat to safety and the person reduces the speed. This behaviour is referred to as car-following behaviour. This is the prevalent form of driving, meaning this is the mode in which drivers are for the largest range of densities (may be from 8 to 10 vehicles per km per lane to about 60 vehicles per km per lane). In the latter parts of this section more is discussed about this important driving behaviour. One may also refer to Chakroborty and Kikuchi [6] for a better exposition.

At the other end of the density scale, where densities are large, vehicles move with frequent halts or near halts. This kind of traffic is referred to as stop-and-go traffic. Driver behaviour in this region is impacted by the vehicles ahead. However, the strength of the relationship is not as strong as in the car-following case; often it is seen that vehicles keep longer than safe distances, vehicles do not immediately respond to spacing increments; etc. It seems that the primary motivator in these cases is only safety and urgency plays a lesser role. Similar observations have been made by others (for example, see Minderhoud and Zurbier [23]). It is felt that very little empirical research has been reported on stop-and-go traffic and more needs to be done to understand the behaviour better. In the rest of the section, the discussion is on models of car-following behaviour.

Over the years various models of car-following have been proposed. An overview of the models can be found in Brackstone and McDonald [24]. Here two of these models are mentioned. The models described here are the GHR models (one of the first set of models in car-following) and the fuzzy rule-based models (one of the most recent developments in this area).

The GHR models [7, 25–27] proposed the following stimulus-response car-following rule:

$$\ddot{x}_{FV}(t+\delta t) = \alpha_{\ell,m} \frac{\{x_{FV}(t+\delta t)\}^m}{\{x_{LV}(t) - x_{FV}(t)\}^{\ell}} \{\dot{x}_{LV}(t) - \dot{x}_{FV}(t)\} \tag{4}$$

where $x_i(t)$ is the position of vehicle i at time t measured from an upstream point, ℓ and m are calibration constants and are the same as those used in Equation 3. This rule with a proper choice of the exponents yields actions which give rise to stability. However, its reliance on only relative speed as the stimulus (the others simply modify the response to the stimulus) gives rise to certain problems; for example, this model cannot replicate the closing-in and shying-away behaviour. For a detailed discussion on this model and its shortcomings one may refer to Chakroborty and Kikuchi [6]; which it should not be. These drawbacks, notwithstanding, what this model showed for the first time was that expressions on the FV's actions could be derived which gave rise to stable behaviour. The authors believe that stability is an important car-following property which every microscopic model of traffic flow must exhibit.

The fuzzy rule-based model of car-following was initially proposed by Kikuchi and Chakroborty [28]. These models form the "latest distinct stage in their development, as it represents the next logical stage in attempting to accurately describe driver behaviour" (Brackstone and McDonald [24]). The fuzzy rule-based model [6, 28, 29] simply models driver behaviour by specifying a set of linguistic rules on what to do under different circumstances. For example, a rule could be: *IF (at time t) the Distance headway is very large AND Relative speed moderately negative AND Acceleration of LV is negative THEN (at time $t+\delta t$) FV should accelerate mildly.*

The results from the model show that all the properties of car-following behaviour are satisfied (see Chakroborty and Kikuchi [6]). The author believes that this model illustrated that simple rules-of-thumb can explain in all details such complicated behaviour as car-following. In this sense, it is felt that rule based structures like the ones that can be employed in cellular automata models can be successful in realistically representing driver behaviour and hence the macroscopic behaviour of the traffic stream.

Before leaving this section it must be pointed out that all models which are in essence microscopic models of traffic flow (like the cellular automata based models) must be subjected to tests which determine whether these models possess the microscopic properties mentioned earlier. Certain car-following properties, like stability, independence of stable conditions from initial conditions and perturbations, etc. are essential for any microscopic model. If a large number of the microscopic properties are absent, then the model's predictions at a macroscopic level also become suspect.

Another point which must be reiterated is that the existing microscopic models of traffic flow ignore lateral interactions. When lane discipline is not maintained or in situations of extensive weaving (merging or diverging of traffic streams like at roundabouts or near on or off ramps) there is considerable lateral interactions between vehicles. In such cases studying the process of longitudinal control of vehicles will not suffice; one has to look at the process of longitudinal and lateral control of vehicles in a comprehensive manner. In fact, models which can account for both lateral and longitudinal interactions between vehicles can in general be used to study the interactions of vehicles with other features of the road like road edges, geometry, static obstacles like parked vehicles, etc. It is felt that such models will provide a basis for relating capacity of roads (or more generally flow behaviour) to engineering features of the road like width, radius of curves, lateral clearance, and the like. Hence, the ultimate goal of modeling traffic flow must be to evolve a model of driver behaviour which can handle both longitudinal and lateral interactions and is simple enough to be used to simulate a large number of vehicles at a time so that macroscopic properties of the road can be studied. In the next section, some recent ideas on modelling both lateral and longitudinal interactions are discussed.

4 Some New Directions to Modelling Uninterrupted Traffic

The final goal in microscopic modelling is to be able to devise a comprehensive model of driver behaviour; a model which under one framework can explain a driver's choice of steering angle and acceleration values under various different driving situations. That is, such models should be able to describe the path of every vehicle over space and time.

Two types of comprehensive models have been developed in the recent past. The first are force field models and the second is a model which combines the concepts of utility-based discrete choice models and longitudinal control models. The force-field based models were developed at IIT Kanpur (for example, see Gupta et al. [30] and Chakroborty et al. [31]). The force field idea was also used by Helbing and Tilch [32] to model traffic dynamics; but the study was limited to only longitudinal control and hence did not contribute towards the development of a comprehensive model as envisaged here. The force-field based comprehensive model [30, 31] of traffic flow relate the steering angle and acceleration values to force (or potential) field in a driver's vicinity and is based on the following simple ideas:

(i) every goal (or "local" destinations like "ahead of the previous vehicle") emanates attractive (or negative) potentials and every other feature on the road (like road edges, parked vehicles, moving vehicles, etc.) are considered as obstacles which emanate repulsive (or positive) potentials,

(ii) the potential at a point on the road is assumed to be the algebraic sum of all the potentials from the various obstacles and goals,

(iii) the potential at a point is perceived as a threat to a driver's safety; the threat increases with speed; hence, it is assumed that the sustainable speed (a speed at which a driver feels comfortable) at a point is inversely related to the potential at that point,

(iv) given that a driver wishes to reach his destination quickly, he chooses the path which minimizes the potential (and hence maximizes the speed),

(v) the acceleration value is related to the potential values and their gradient along the chosen path and in some sense embody the notions of longitudinal control models.

These models are computationally intensive and therefore limited in their application for simulating large streams. Some work is on going at IIT Kanpur to develop a comprehensive model which is computationally efficient and yet reasonably realistic in its representation of a stream both microscopically and macroscopically.

A preliminary version of such a model has been developed and named CUTSiM (Comprehensive, Unidirectional, Uninterrupted Traffic Simulation Model). This model assumes that drivers choose a path based on various properties of that path like, headway available, closeness to obstacles, difficulty of re-orienting the vehicle to that path, etc. Once this choice is made, drivers drive along that path using principles similar to those used for longitudinal control model described earlier. CUTSiM incorporates the impact of geometry (so far only in terms of road width) and vehicle mix while simulating a traffic stream; further CUTSiM does not assume lane discipline. Even so, it has been shown that under certain conditions of "choice parameters" vehicles can be made to follow "lanes [33]." It is shown that CUTSiM satisfies most of the microscopic and macroscopic properties of traffic streams described earlier and is also computationally efficient. For example, CUTSiM can simulate traffic streams with upward of 4000 vehicles for an hour in less than 30 minutes on a desktop computer with dual core 2.2 GHz processor and 32 GB RAM.

Some macroscopic results from CUTSiM are presented here to illustrate its ability to incorporate the impact of road width and vehicle-mix on stream behaviour and also to show that it can model streams without lane discipline reasonably well. The model and its detailed analysis will be presented in a forthcoming paper based on Maurya [33]; details of a primitive version of CUTSiM can be found in Maurya and Chakroborty [34]. Figure 2 shows three speed-flow scatter plots obtained from streams simulated using CUTSiM; on comparing (a) and (b) parts of the figure one can see that as the lane width reduces the speed-flow relations obtained from streams simulated using CUTSiM also changes and the maximum flow reduces. On comparing (a) and (c) one can see that as the percentage of trucks is increased the stream behaviour also changes and the maximum flow in vehicles per hour (vph) falls; another interesting feature is that at low flow values the effect of trucks on stream behaviour is much less pronounced than at high flows as is expected. Figure 3 shows a comparison of the speed-flow data collected from Delhi-Gurgaon Highway in India (road width = 14.6 m; no lane discipline) with those obtained

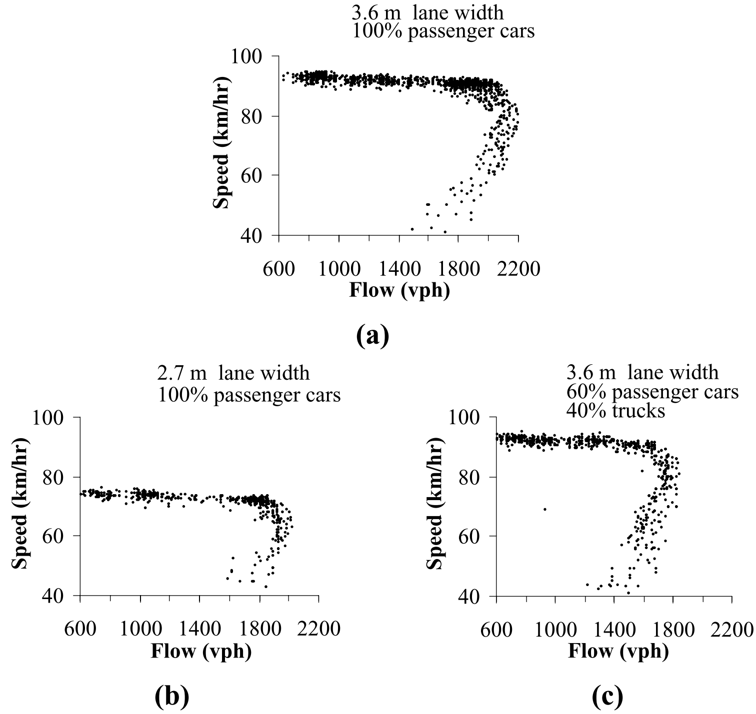

Fig. 2. Speed-flow data obtained from streams simulated using CUTSiM for different lane widths and vehicle-mix.

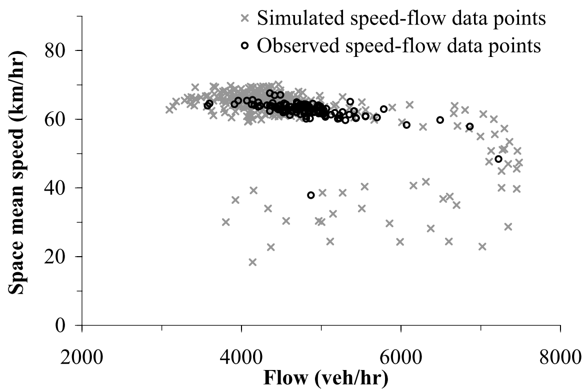

Fig. 3. Comparison of speed-flow data obtained from Delhi-Gurgaon Highway (road width = 14.6 m, no lane discipline) with those obtained from a CUTSiM simulated stream.

from a stream simulated using CUTSiM for the same conditions as those on the Delhi-Gurgaon Highway. As can be seen the match is good.

5 Summary

The purpose of the paper was to highlight (i) the importance of flow models to traffic engineers who often cannot conduct experiments to see the impact of certain design alternatives on traffic behaviour, and (ii) the ingredients needed in a model of traffic flow for it to be really useful for traffic engineering purposes. It was mentioned that developing models which can incorporate both lateral and longitudinal interactions from both roadway and traffic features should be the ultimate goal of the exercise of traffic flow modelling. Some new models which attempt to achieve this goal were also briefly discussed.

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