Current Natural Sciences

INTELLIGENT TRANSPORTATION SYSTEM

Junfang TIAN and Rui JIANG

Car Following Dynamics: Experiments and Models

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Over the past nine decades, the field of traffic flow studies has witnessed remarkable advancements driven by empirical data. These data have illuminated traffic phenomena like breakdowns, oscillations, and hysteresis. However, despite these strides, the intricate nature of traffic flow and its underlying mechanisms remain subjects of ongoing debate and incomplete comprehension. Robert Herman, the pioneering figure in transportation science, firmly believed in the experimental essence of traffic theory. Unlike conventional practices of collecting limited traffic flow data, conducting traffic experiments empowers control of flow composition and rate, minimizes interference from complex variables, and facilitates the discovery of fundamental characteristics and mechanisms of traffic flow.

In alignment with Herman's conviction, the authors of this book undertook a series of experimental and modeling studies to delve into the intricacies of traffic flow evolution through the lens of car-following dynamics. Rooted in systems science and engineering theory, this book commences with experimental exploration of traffic flow. Employing methods to unearth individual decision-making mechanisms, the evolutionary patterns of group behavior, and their interconnectedness, theoretical models are employed to bridge micro-mechanisms with macro-phenomena. This approach introduces innovative ideas and methods, fostering the refined development of urban traffic behavior and management theory. It makes vital contributions in unraveling driver behavior and the evolution of road traffic flow, transcending conventional theories, and addressing globally recognized transportation challenges. Ultimately, it plays a pivotal role in advancing modern traffic flow theory that aligns with real-world complexities.

This book serves as an essential reference for students, educators, and professionals in engineering and transportation sciences, offering comprehensive insights into traffic flow studies.

Junfang TIAN, a distinguished researcher at the Institute of Systems Engineering, College of Management and Economics, Tianjin University, specializes in traffic flow theory, transport policy, and travel behavior analysis. Rui JIANG, a professor at the School of Systems Science, Beijing Jiaotong University, focuses on traffic flow theory, travel behavior analysis, and transportation network analysis.

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Preface

The development of traffic flow studies has been almost 90 years since the publication of the seminal Greenshields model. Many traffic phenomena, such as traffic breakdown, traffic oscillations, and hysteresis, have been observed. Hundreds of traffic flow models have been developed to explain and simulate the observations. Some models have been successfully used in transportation engineering applications. However, despite the achievements, the evolution mechanism of traffic flow has not been fully understood, and controversies exist in traffic flow theories. As a consensus, this is largely due to the lack of large-scale high-fidelity traffic data without gaps in information.

The traditional way to collect traffic flow data comes by observing traffic flow passively. Such data have great limitations because the traffic flow is uncontrollable. Moreover, the empirical observations are quite site-specific and contain many confounding factors. On the other hand, *via* traffic experiments, one can control the traffic flow composition and flow rate, reduce the interference of complex factors, and expect to discover the essential characteristics and mechanism of traffic flow evolution.

The complexity of traffic flow evolution is mainly from a car following dynamics and lane-changing behavior. This book offers an account of the car's following dynamics, from the aspect of experiment as well as modeling. The context has been documented in specialized scientific papers, and we hope it can be accessed by a broader readership.

This book consists of six chapters. Chapter 1 is an introduction to the state-of-the-art of traffic flow studies, chapter 2 mainly presents experimental findings of traffic oscillations. Chapter 3 analyzes the car following behaviors. Chapter 4 presents the cellular automaton models and chapter 5 presents the car following models. Finally, the conclusion and outlook are given in chapter 6.

The book is expected to serve as a reference guide on issues of traffic flow studies for students, lecturers, and professionals of engineering and transportation sciences.

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Chapter 1

Introduction

From the bird's-eye view, the movements of vehicles on the road have fluidity as gas or liquid, thus it is named the traffic flow, which can be characterized by flow, speed, density, etc. Due to the complexity of traffic flow, its evolution mechanism is still not clear. In this chapter, the motivation for traffic flow experiments is discussed. Then two typical types of data used in traffic flow studies, *i.e.*, the vehicle trajectory data and the detector data, are introduced. The fundamental parameters of traffic flow and the fundamental diagram are also introduced. Finally, the empirical characteristics of traffic flow evolution are explained, including congested traffic, phantom jam, synchronized traffic flow and traffic breakdown.

1.1 Background

Traffic congestion has become a worldwide problem, especially in China, due to the process of fast urbanization. It is not sustainable to mitigate traffic congestion *via* increasing transport infrastructure. Scientific theories should be established to improve the operation efficiency of transportation facilities.

Traffic flow theory studies the travel behavior of traffic participants and the spatiotemporal evolution of traffic flow. Based on traffic flow data analysis, this theory describes the characteristics and phenomena of traffic flow, and establishes models which could simulate and predict spatiotemporal patterns of traffic flow. Finally, these models will be used for practical traffic management and control, which aims to provide solutions to alleviate traffic congestion.

With the development of traffic flow studies, some nonlinear dynamics characteristics of traffic flow have been discovered. However, the evolution mechanism of traffic flow has not been fully understood. In particular, the three-phase traffic theory and the fundamental diagram theory are highly controversial. For example, Schönhof and Helbing (2009) published a paper titled "Criticism of three-phase traffic theory", and Kerner (2013) published a paper titled "Criticism of generally accepted fundamentals and methodologies of traffic and transportation theory–A brief review".

It's worth mentioning that in both theories, the sophisticated evolution of traffic flow is closely related to the instability or metastability of traffic flow. In contrast, in

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LWR theory, the sophisticated evolution of traffic flow is usually attributed to "geometric constraint", *i.e.*, different external bottlenecks.

The main difficulty to resolve this controversy is a lack of high-fidelity traffic data that covers congestion from its birth to its death without gaps in information. Most of the data are currently available are collected by point sensors (*e.g.*, loop detectors), and the distance between two neighboring sensors is usually 1–3 km for most freeway sections showing recurrent congestion patterns. As claimed by Treiber *et al.* (2010), "*this is of the same order of magnitude as typical wavelengths of non-homogeneous congestion patterns*" and therefore definitely leads to a loss of information pertaining to the finer features of traffic flow. Daganzo *et al.* (1999) also pointed out that "*no empirical studies to date describe the complete evolution of a disturbance*" and thus we cannot "*explain the genesis of the disturbances or the rate at which they grow*".

The traffic science community has also realized the importance of precise traffic data. As Schönhof and Helbing (2009) claimed, "*In order to finally decide which traffic model provides the best description and what is the true cause of the spatiotemporal organization of the general pattern, it is necessary to have spatiotemporal data of single vehicles ... they will be needed to shed more light on the oldest and most central question of traffic theory, namely what are the real mechanisms and quantitative properties of traffic breakdowns.*"

Studies of this kind could be expensive and technologically challenging. For example, Knoop *et al.* (2008) collected empirical data from a helicopter, using a digital camera to gather high-resolution monochrome images. However, the images cover only 280 m of the motorway and due to the limited stability of the helicopter, only 210 m of the motorway could be used for vehicle detection and tracking. Similarly, the NGSIM data cover only several hundred meters of the highway, which is also very limited.

The traditional way of collecting traffic flow data comes by observing traffic flow passively. Such data have great limitations because the traffic flow is uncontrollable. A common way to test traffic flow models is to examine the spatiotemporal patterns induced by an isolated bottleneck by tuning the bottleneck strength and inflow rate. However, in practice, it is not easy to find an isolated bottleneck. Moreover, neither the bottleneck strength nor the inflow rate can be controlled.

Moreover, the empirical observations *via* cameras are quite site-specific and contain many confounding factors (*e.g.*, geometry such as on-ramps, off-ramps, and weaving area, bottleneck strength, traffic flow composition), which makes it difficult to isolate the dynamical behavior of car-following from those of lane-changing and other interactions. As a result, although there are vast amounts of empirical data, we are unfortunately still unable to understand how traffic dynamics evolve even in very simple scenarios.

Due to the limit of traffic observations, traffic experiments have attracted the interest of researchers. *Via* traffic experiments, one can control the traffic flow composition and flow rate, reduce the interference of complex factors, and extract the essential factors for traffic breakdown, *e.g.*, by performing the experiment near an isolated traffic bottleneck. Thus, one can expect to discover the essential characteristics of traffic flow evolution.

For example, Japanese researchers have conducted several controlled traffic flow experiments on circular roads (Sugiyama *et al.*, 2008). The result shows that even in a circular road without bottlenecks, congestion may occur spontaneously. Their research demonstrates the important role of experimental methods in the study of traffic flow evolution.[1]

We would also like to point out that experimental methods play an important role in complex system research. For example, in the studies of pedestrian flow and the group behavior of animals like ants, experimental methods are broadly applied, which promotes the development of this research.

1.2 Traffic Flow Data

1.2.1 Vehicle Trajectory Data

On the plane, (t, x) or (x, t), vehicle trajectory is the curve representing the corresponding relationship between time t and vehicle position $x(t)$. In general, the trajectory only describes the longitudinal motion of the vehicle and does not contain information about the lateral position and direction of the vehicle. From the vehicle trajectory diagram, not only can we obtain the microscopic information, such as time headway, distance headway and speed, but also can get the macroscopic information of traffic flow operation, such as volume, density, and roadway occupancy rate. For example, the first derivative of the trajectory yields the velocity of the vehicle ($v = dx/dt$), and the second derivative yields the acceleration of the vehicle ($a = d^2x/dt^2$). As shown in figure 1.1, a blue curve shows a vehicle moving forward, stopping for some time, and then moving on. Figure 1.1 shows that the traffic jam gradually forms and propagates upstream. The propagation speed w of the jam can also be identified.

1.2.2 Detector Data

Detector data are usually collected by loop detectors at a fixed location on the road, which are one of the earliest and most proven detection technologies. When a vehicle passes the loop, the vehicle causes a change in the inductance of the signal, so that the arrival and departure of the vehicle can be detected, see figure 1.2.

The detector can directly measure the following variables:

(1) The moment when the front bumper of the vehicle passes the detector $t = t_1$;
(2) The moment when the rear bumper of the vehicle passes the detector $t = t_2$.

[1]Note that as early as in the 1950's, Chandler *et al.* (1958) conducted the car-following experiment, aiming to calibrate the parameters of car-following model and evaluate the model performance.

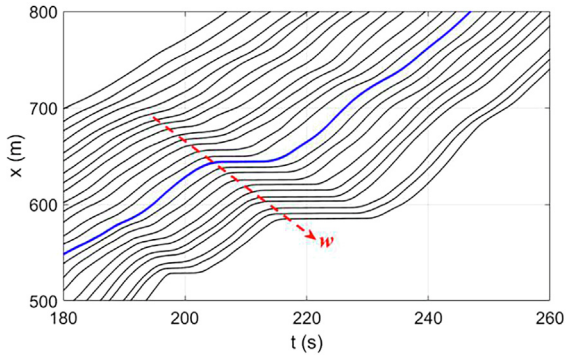


FIG. 1.1 – Vehicle trajectory.

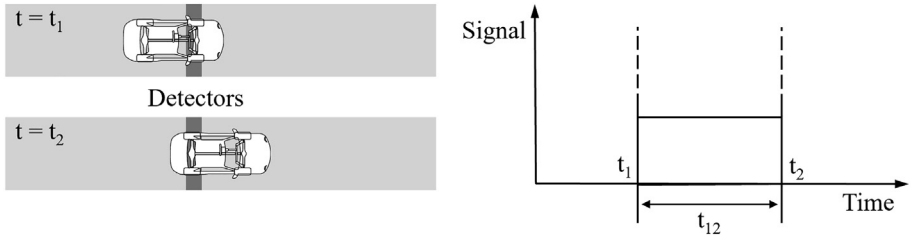


FIG. 1.2 – The illustrations of the loop detector.

It is impossible to obtain important information such as vehicle speed through only one detector, so the double-detectors are often used as a group on the road, and the distance between the two detectors is very close, such as 1 m. Assuming the vehicle moves with constant speed between the two detectors, the vehicle speed v can be calculated based on the time difference of the vehicle passing the two detectors. Based on these variables, the following variables can also be calculated:

(1) Vehicle length l_{veh}: $l_{\text{veh}} = v(t_2 - t_1)$.
(2) Vehicle type: vehicle type can be determined by vehicle length.
(3) Time headway (h): the time difference between the front bumper of two consecutive vehicles arriving at the detector.
(4) Time gap (g): the time difference between the rear bumper of the leading vehicle and the front bumper of the following vehicle.
(5) Space headway (s): the distance between the front bumper of two consecutive vehicles, $s = vh$.
(6) Space gap (d): the distance between the rear bumper of the leading vehicle and the front bumper of the following vehicle, that is space headway minus the length of the front vehicle, $d = s - l_{\text{veh}}$. The calculation of vehicle length, headway, and vehicle spacing assumes that vehicles move with constant speed.

1.3 Traffic Flow Parameters

Flow rate q, speed v and density ρ are the three basic parameters that characterize the macroscopic characteristics of traffic flow.

1.3.1 Flow Rate

(1) Flow rate q: the number of vehicles passing a fixed location on the roadway in unit time,

$$q = \frac{N}{T} \tag{1.1}$$

where T is the observation time interval and N is the number of vehicles passing the location during the interval.

According to the definition of headway, the observation interval T is equal to the sum of the time headways of all vehicles passing during this period, that is $T = \sum_{i=1}^{N} h_i$. Therefore, the flow rate can also be formulated as follows:

$$q = \frac{N}{T} = \frac{N}{\sum_{i=1}^{N} h_i} = \frac{1}{\frac{1}{N}\sum_{i=1}^{N} h_i} = \frac{1}{h} \tag{1.2}$$

where h is the meantime headway.

1.3.2 Density and Occupancy

Density (ρ) is the number of vehicles in a unit length of roadway.

$$\rho = \frac{N}{L} \tag{1.3}$$

where N and L mean the number of vehicles and length of the road section, respectively. Therefore, it is not possible to measure the density directly with detectors.

Occupancy is the ratio of time that vehicles occupy a detector to the observation time interval, which can be expressed as follow:

$$\text{occupancy} = \frac{\sum_{i=1}^{N} (L_i + l_{\text{det}}) \Big/ v_i}{T} = \frac{1}{T}\sum_{i=1}^{N} \frac{L_i}{v_i} + \frac{l_{\text{det}}}{T}\sum_{i=1}^{N} \frac{1}{v_i} \tag{1.4}$$

where v_i and L_i are the speed and length of the vehicle i respectively, l_{det} is the size of the detector.

1.3.3 Speed

As mentioned before, speed is the first derivative of the trajectory

$$v = \frac{dx}{dt} = \lim_{(t_2 - t_1) \to 0} \frac{x_2 - x_1}{t_2 - t_1} \tag{1.5}$$

where t_1 and t_2 are two consecutive measurement times, x_1 and x_2 are the positions of the vehicle at time t_1 and t_2 respectively.

In practical applications, the average vehicle speed is widely used. There are two commonly used methods to calculate average vehicle speed: arithmetic average and harmonic average.

(1) Arithmetic average method: average vehicle speed is calculated as follows:

$$\overline{v}_t = \frac{1}{N}\sum_{i=1}^{N} v_i \tag{1.6}$$

where v_i is the speed of vehicle i.

However, this method has a deficiency. Since we calculate traffic density *via* $\rho = q/\overline{v}_t$, the high density is usually underestimated. This is because the arithmetic average method gives the time average speed, while average speed in the relation $q = \rho\overline{v}$ refers to the space average speed.

(2) Harmonic average method: average vehicle speed is calculated as follows:

$$\overline{v}_s = \frac{1}{\frac{1}{N}\sum_{i=1}^{N}\frac{1}{v_i}} \tag{1.7}$$

As above mentioned, the traffic density can be obtained by the equation: $\rho = q/\overline{v}_s$. The attainable range of density calculated by the harmonic average method is much higher than that of the arithmetic average method. However, the harmonic average method also has the deficiency that it is highly sensitive to the measurement error of low speed.

1.4 Fundamental Diagram

1.4.1 Homogeneous, Stationary and Equilibrium Traffic Flow

In homogeneous traffic flow, the parameters (such as speed, density, flow rate, etc.) do not change with location. In stationary traffic flow, the characteristic parameters do not change with time. The homogeneous and stationary traffic flow is called the equilibrium traffic flow.

1.4.2 The Fundamental Diagram

In traffic flow theory, it is usually assumed that the three basic parameters of traffic flow in an equilibrium state have the following relationships: