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Traffic dynamics: Its impact on the Macroscopic Fundamental Diagram

Victor L. Knoop *, Hans van Lint, Serge P. Hoogendoorn

Delft University of Technology, Transport & Planning, Stevinweg 1, 2628 CN Delft, The Netherlands

HIGHLIGHTS

- Production is a continuous function of accumulation and inhomogeneity of density.
- The MFD is a two-dimensional projection of this plane.
- Traffic dynamics lead to a path through the plane of accumulation and inhomogeneity of density.
- In the NFD the path on the continuous production plane is shown as hysteresis.

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ABSTRACT

Literature shows that – under specific conditions – the Macroscopic Fundamental Diagram (MFD) describes a crisp relationship between the average flow (production) and the average density in an entire network. The limiting condition is that traffic conditions must be homogeneous over the whole network. Recent works describe hysteresis effects: systematic deviations from the MFD as a result of loading and unloading.

This article proposes a two dimensional generalization of the MFD, the so-called Generalized Macroscopic Fundamental Diagram (GMFD), which relates the average flow to both the average density and the (spatial) inhomogeneity of density. The most important contribution is that we show this is a continuous function, of which the MFD is a projection. Using the GMFD, we can describe the mentioned hysteresis patterns in the MFD. The underlying traffic phenomenon explaining the two dimensional surface described by the GMFD is that congestion concentrates (and subsequently spreads out) around the bottlenecks that oversaturate first. We call this the nucleation effect. Due to this effect, the network flow is not constant for a fixed number of vehicles as predicted by the MFD, but decreases due to local queueing and spill back processes around the congestion "nuclei". During this build up of congestion, the production hence decreases, which gives the hysteresis effects.

1. Introduction

The dynamics of traffic differs considerably from many other transport phenomena. Most striking is that if the load (i.e., number of vehicles) exceeds a critical number, the traffic performance, for instance measured by arrival rates, decreases with an increasing traffic load. This differs for instance from fluid dynamics where a higher load leads to higher flows. In this article we will study how traffic dynamics evolve in a traffic network, and how this influences macroscopic traffic variables.

* Corresponding author.
E-mail address: v.l.knoop@tudelft.nl (V.L. Knoop).

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The concept of describing the traffic dynamics for a zone, consisting of several roads is appealing and possibly a very powerful tool. The idea that the speed of the vehicles depends on the number of vehicles dates back to the sixties [1]. Similar findings are presented later [2,3], and the research gained momentum after Daganzo reintroduced the concept [4] and Geroliminis and Daganzo showed the application using real world data [5]. They call it the Macrosopic Fundamental Diagram (MFD), and show that aggregated over an area, the relationship between accumulation (i.e., the average density of roadway length) and production (i.e., the average flow of vehicles per unit of time) is quite crisp. This can be an aspect of the law of large numbers: the more data is aggregated, the less influence the differences in drivers characteristics have. For control purposes, it is very useful to have a strict relationship on the basis of which control can be applied. However, several research efforts after [5] (e.g., Refs. [6,7]) suggest that such a crisp relationship exists only for homogeneously loaded networks.

The papers handling the inhomogeneity usually do not comment on the cause of the inhomogeneity, which lies in the traffic dynamics in networks. In fact, traffic dynamics in congested networks inherently leads to traffic inhomogeneity, because, under increasing traffic volume loaded onto the network at some point congestion will set in at one of the (potentially many) bottlenecks in a network. This will lead to an inhomogeneous distribution of vehicular density in the network, with congestion in one part of the network and still freely flowing traffic in the remaining parts.

This process influences the network performance for the same accumulation. To still have a description of the traffic performance in a zone, we propose a generalization of the MFD, the Generalized Fundamental Diagram (GMFD), which describes the traffic production as a continuous function of both the average density (accumulation) and the spatial spread of density. This latter quantity can be interpreted as an average measure for inhomogeneity of traffic conditions. We will demonstrate that this GMFD describes a well-defined (crisp) two dimensional plane. The classic MFD, as a function of vehicle accumulation only, is a one-dimensional projection of this plane.

The use of this paper is twofold. At one hand, its scientific use is that it makes clear the that production is a *continuous* function of accumulation and spatial inhomogeneity of density. It also, after the analysis of simulated traffic dynamics in a network, describes hysteresis effects found in the MFD using the GMFD. At the other hand, for practical use, this newly found GMFD can be used in traffic control schemes. For instance, it can be used for estimating speed in a (sub-) network, and traffic can be guided over the faster routes. This way, GMFD can improve traffic control concepts, based on the MFD, e.g. Refs. [8–11].

The remainder of the article is set-up as follows. First, a review is provided of the literature of the MFD. Then, Section 3 introduces the variables used in this article. Section 4 then presents how GMFDs look when traffic dynamics are not incorporated. We do so by simply averaging randomly chosen traffic states. Section 5 presents the simulation experiment. Using a macroscopic traffic simulation, a simplified traffic network is simulated, and the queueing dynamics are analysed. Furthermore the effect of the spatial inhomogeneity of density on the GMFD of density is studied in detail. Section 6 explicitly compares the GMFD of the traffic simulation with GMFD obtained by randomly chosen traffic states, and explains the differences in results. Thus, we are able to comment on the effect of traffic dynamics on the GMFD. Finally, Section 7 presents the conclusions and an outlook on further research and applications.

2. The Macroscopic Fundamental Diagram and inhomogeneity

Original ideas on the MFD [1,3] described that traffic speeds decrease with increasing accumulation. The recent increase of attention came after Daganzo [4] reintroduced the concept and showed how the production could decrease if accumulation increases. The name Macroscopic Fundamental Diagram has been proposed by Geroliminis and Daganzo [5]. In their paper they showed, based on data, that the traffic flow decreases after the accumulation increased over a critical threshold. These papers give a snapshot situation of traffic and do not account for the dynamics or heterogeneity.

Heterogeneity is explicitly studied by Buisson and Ladier [6], creating the MFD in heterogeneous situations. They found, using data from three different days in the French city of Toulouse, that the MFD does not hold in heterogeneous conditions.

The explanation for the reducing production is also described. First, the effect of inhomogeneity is further discussed by Mazloumian et al. [12] and Geroliminis and Ji [7]. First, Mazloumian et al. [12] show with simulation that the spatial inhomogeneity of density over different locations is an important aspect to determine the total network production. So not only too many vehicles in the network in total decrease the network performance, but also if they are located at some shorter jams at parts of the networks. The reasoning they provide is that "an inhomogeneity in the spatial distribution of car density increases the probability of spillover, which substantially decreases the network flow". Furthermore, they conclude that it is essential to model flow quantization to obtain the effects of reducing performance with an increasing variability. This finding from simulation and reasoning is then confirmed by an empirical analysis [7], using the data from the Yokohama metropolitan area. The main cause for this effect is claimed to be the turning movement of the individual vehicles. The same data is used by Geroliminis and Sun [13] showing that if clustered in bins with similar variation of density, the MFD is a well defined curve. Daganzo et al. [14] simplify the setup and approach the traffic flows and MFDs analytically. They show there are several equilibria to which the network will relax if loaded. Where they do show the equilibrium points, they do not show the direct influence of density variability on network production.

A theoretical explanation for the phenomenon of the influence of the spatial inhomogeneity of density on the accumulation is given by Daganzo et al. [14]. They show that turning at intersections is the key reason for the drop in production under spatially inhomogeneous conditions. Gayah and Daganzo [15] then use this information by adding