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# Calibration of fundamental diagram using trajectories of probe vehicles: Basic formulation and heuristic algorithm

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**Abstract**

A fundamental diagram (FD), also known as flow–density relation, is one of the most important principles in traffic flow theory. It would be valuable if an FD could be calibrated by using GPS-equipped probe vehicles; since they can continuously collect data from wide spatiotemporal area, compared to traditional fixed sensors. This paper proposes methods for calibrating an FD from trajectories of sampled vehicles. We formulate a method that identifies values of a free-flow speed and a critical density of a tri-angular FD, while it relies on exogenous assumptions on FD's functional form and a value of its jam density. Then, a heuristic algorithm for FD calibration in actual traffic environment is developed based on the proposed method. It was validated using traffic data generated by microscopic traffic simulator. The results suggested that the proposed methods can calibrate an FD precisely and robustly. It implies that FDs in road sections on which congestion happens frequently can be calibrated using probe vehicles, if probe vehicle data were collected for a long period. Therefore, the proposed methods would contribute to significant improvement of applicability of probe vehicle-based traffic management methods.


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*Keywords:* traffic flow theory, fundamental diagram, GPS-equipped probe vehicle, trajectory

## 1. Introduction

*Fundamental diagram (FD)*, also known as flow–density relation, is literally one of the most fundamental concepts in the traffic flow theory. An FD describes relation between flow and density [2] in *stationary traffic*.

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Stationary traffic is defined as traffic in which all the vehicles have the same constant speed and spacing (Daganzo, 1997). In theory, an FD itself contains useful information on traffic features, such as value of free-flow speed and flow capacity, and distinction between free-flow and congested states. Empirical studies also showed that clear relation can be found between flow and density in actual traffic at near-stationary states (Cassidy, 1998). In addition, macroscopic traffic flow dynamics can be modeled by combining an FD and other principles: the most known example is the Lighthill–Whitham–Richards (LWR) model (Lighthill and Whitham, 1955; Richards, 1956). Moreover, FDs can describe microscopic vehicle behavior to some extent (Newell, 2002). Therefore, FDs are applied to various academic and practical purposes in traffic and transportation engineering, such as macroscopic traffic simulation (e.g., Daganzo, 1994), traffic control (e.g., Papageorgiou et al., 2003), and traffic state estimation (e.g., Deng et al., 2013).

To calibrate parameters of an FD in actual traffic, one has to collect data from traffic, to assume its FD's functional form, and then to calibrate the FD's parameters by fitting the FD to the data. Those data are commonly collected using fixed sensors (e.g., cameras, detectors) from the era of Greenshields (1935); for example, see Chiabaut et al. (2009), Dervisoglu et al. (2009), Coifman (2014), and references therein. This is a straightforward way because usual fixed sensors can measure traffic count and occupancy, which are closely related to flow and density, respectively, at their location. The limitation of the fixed sensor-based calibration is obvious: it cannot calibrate FDs where sensors are not installed. Therefore, FDs on roads without sensors, such as most of arterial roads, are difficult to be known. Identification of bottlenecks' exact locations and characteristics is also difficult, even on freeways with some sensors.

*Probe vehicles* received high attention in these days.[3] The advantage of probe vehicles is their significantly wider data collection range (in spatiotemporal domain) compared with fixed sensors (Herrera et al., 2010). For example, one of the most typical and useful utilization of the advantage is traffic state estimation, which estimates flow, density, and speed of traffic using partial measurement data (c.f., Deng et al., 2013, and references within). However, existing studies on such application assume their FDs exogenously, in order to relate flow and density to speed measured by probe vehicles. This can be significant limitation for application of probe vehicles, since FD calibration is not a trivial task. Especially, FD calibration using probe vehicle data has been not well studied. Appendix in Herrera et al. (2010) mentioned a manual inference method for FD using probe vehicle data under special conditions. However, it lacks rigorous formulation and is not computable. Considering these days high availability of probe vehicle data, systematic and computational approaches for FD calibration would be desirable.[4]

The aim of this paper is to propose a method of calibrating FDs using probe vehicle data. In order to enable the calibration, we allow the method to rely minimum exogenous assumptions, such as FD's functional form and values of some of the FD's parameters (e.g., jam density which can be inferred from external knowledge). In addition, to show empirical validity of the proposed method, a computable method for FD calibration is developed and validated using microscopic traffic simulation data.

The rest of this paper is organized follows. Section 2 formulates a method of identifying FD parameters using sampled vehicle trajectories under idealized conditions. Section 3 describes a heuristic algorithm for actual traffic environment based on the proposed method. Section 4 validates the proposed heuristic algorithm using noisy traffic data generated by microscopic traffic simulation. Section 5 concludes this paper.

## 2. Formulation

This section describes a method of calibrating FD using sampled vehicle trajectories under simplified conditions.

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[2] Technically, relation between two variables among flow or headway, density or spacing, and speed or pace (Laval and Leclercq, 2013).

[3] In this paper, unless otherwise specified, the term "probe vehicle" refers to be the Global Positioning System (GPS)-equipped probe vehicle, which continuously measure and report its position and time.

[4] If probe vehicles can measure spacing to their leading vehicles using advanced technologies (c.f., Huber et al., 1999; Seo et al., 2015a), FDs can be directly derived from such probe vehicle data in detail, for example, continuously (Kotani and Iwasaki, 1999), individually (Duret et al., 2008), stochastically (Jabari et al., 2014), and jointly with traffic state (Seo et al., 2015b). However, these technologies are not commonly available for large-scale data collection at this moment. Therefore, application of such advanced technologies is out of scope of this study.