Introducing the Platoon Fundamental Diagram for Automated Vehicles based on large-scale empirical observations

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SHORT SUMMARY

The interest in understanding the coordinated behavior of car-platoons and their impact on traffic efficiency, safety and energy demand is high. Recently, real-world experiments towards observing car-platoons with ACC-driven vehicles became available. Literature highlights that such car-platoons are string unstable, energy inefficient and potentially safety critical. However, few studies link their behavior at microscopic level to the macroscopic impact on traffic. In this paper, we propose a novel model, namely the Platoon Fundamental Diagram (PFD), that creates explicitly such a link. We validate PFD through worldwide experimental observations and we show that PFD can be reliably used as a means of cross-comparison between platoons with automated vehicles. Furthermore, we present evidence about the invariability of PFD to heterogeneity, i.e. the number of vehicles in the platoon, the order of vehicles, the vehicles' powertrains, the vehicle brands or models within the car-platoon, the particularities of the road infrastructure and the data acquisition methods.

Keywords: Adaptive Cruise Control, Platoon Fundamental Diagram, Traffic Flow, Connected and Automated Vehicles, Intelligent Transportation Systems.

1. INTRODUCTION

Traffic investigations started almost 90 years ago aim to gain deeper understanding on complex phenomena in road transport systems. Greenshields in 1933 noticed a linear relation between speed and traffic density and a parabolic relation between speed and traffic flow using the assumption that traffic flow equals to traffic density multiplied by speed, also known as Fundamental Diagram (FD). Since then, numerous studies in the literature exploit the FD as a congestion modeling tool at a macroscopic scale for aggregated traffic micro-dynamics. Decades later, (Geroliminis & Daganzo, 2008; Daganzo & Geroliminis, 2008) demonstrated through observations and analytically described the existence of a macroscopic fundamental diagram, i.e. MFD (also referred as network fundamental diagram, i.e. NFD) for a complete urban network.

At local level, the behavior of vehicle platoons is under study since for over 50 years ago (see (Treiterer & Taylor, 1966)) Approaching our times, the possibility of automated vehicle movement and the concept of platoon of such vehicles in highways is a topic in literature for almost 30 years now, see (Ioannou, 1997). Simulation studies indicate significant benefits in the traffic flow with the deployment of Cooperative Adaptive Cruise Control (CACC) systems, but since empirical observations with CACC-driven vehicles are scarce, solid conclusions can not be reached.

In the past decade, the commercial deployment of Advanced Driver Assistance Systems (ADAS) paves the way for a large number of theoretical but also empirical studies focusing on the new unprecedented behaviors and patterns that such systems will create on public roads. Adaptive Cruise Control (ACC), Cooperative-ACC (CACC) are considered the predecessor of (Connected and) Automated Vehicles regarding their expected longitudinal behavior. Most research works focus on the operation of ACC, i.e. generated dynamics, energy demand, string stability, hysteresis and safety (see (Makridis, Mattas, Ciuffo, Re, et al., 2020; Makridis, Mattas, & Ciuffo, 2020; Brunner, Makridis, & Kouvelas, 2021; Li, Chen, Zhou, Laval, & Xie, 2021; Gunter et al., 2021; Ciuffo et al., 2021). Despite some recent efforts, see (Chen, Ahn, Chitturi, & Noyce, 2017), the impact (positive or negative) at a macroscopic level of ACC enabled vehicles remains unclear.

This paper builds on the operational property of commercial ACC (and CACC) systems to aim for constant headway policy and describes a simple but intuitive model, the Platoon Fundamental Diagram (PFD). PFD provides information on the platoon efficiency at traffic level and facilitates cross-platoon comparisons. It works on platoon level, i.e. fixed number of vehicles and dynamic platoon length. It utilizes the speed measurements to compute the production of the platoon, in a similar way as the flow measurements were used to compute the production for the MFD, see (Geroliminis & Daganzo, 2008). The proposed model produces three quantities, namely the platoon production, the platoon density and the platoon flow. These quantities are normalized per vehicle, hour and kilometer, thus enabling assessment per vehicle and platoons as short as with only two vehicles. Turning the focus from the link to the platoon, simplifies a lot the computations, since the detection of an area with stationary conditions is not necessary anymore. For the PFD, each time observation can be considered an approximation of stationary conditions and therefore PFD can be computed directly on the time domain. In order to test the proposed model, this work analyzes a large number of available observations from the literature (see (Makridis, Mattas, Anesiadou, & Ciuffo, 2021; Gunter et al., 2021)). The aggregated observations include experimental campaigns with very different specifications such as variable number of vehicles in the platoon, homogeneous and heterogeneous platoons, different power-trains, test environments and data acquisition systems.

2. Platoon Fundamental Diagram

It is well-known that the inverse of headway at microscopic level is related to the traffic flow and the inverse of spacing to the density. In order to relate microscopic with macroscopic dynamics, the most common way in the literature to aggregate raw movement data is to use the Edie's generalized definitions for flow, density and speed, see (Edie, 1965; Cassidy & Coifman, 1997). This methodology assumes the existence of stationary conditions, that by definition, are difficult to detect and isolate in platoon vehicle trajectories. An efficient way to maximize the chances of detecting stationary conditions is the work by (Laval, 2011).

Instead of assessing the traffic at link level, we propose a tool for assessment at platoon level. The efficiency at platoon level is by conceptualization linked to a more efficient traffic flow. Platoon vehicle observations usually contain information for the position of each vehicle and their speed at every discrete time instance. Presently, the speed information can give us the production of the platoon at each time instance based on the vehicles' speed at the previous instance. This information, similarly to the MFD description in (Geroliminis & Daganzo, 2008) can enable us work on the time domain, since the space domain is fixed and known, i.e. the number of vehicles in the platoon. Also, conceptually, each time instance corresponds to stationary conditions (with regard to our platoon reference). In the PFD concept, the number of vehicles remains constant and the space is dynamically defined by the distance between the leader and the last vehicle in the platoon. Computations can be performed at every time step, which simplifies a lot the processing part. Please note that the PFD model ignores the leading vehicle of the platoon (there is no information about preceding vehicles). This enables us aggregate experiments in the literature where the leading vehicle was either a controlled driving cycle or a human driver, without compromising the derived PFD.

As already mentioned, since in most experiments there is accurate (offline) information about the speed of the vehicle(s), the production of the platoon between time $t-1$ and t is known and it can be computed as follows:

$$\mathbf{p}(\mathbf{t}) = \frac{\sum_{i=2}^{\mathbf{N}} \mathbf{v}(t-1)}{\mathbf{N}-\mathbf{1}} \tag{1}$$

where $\mathbf{t}$ is the discrete time and $\mathbf{N}$ is the number of vehicles in the platoon. Please note that in the above equation the leader of the platoon is not considered.

Similarly, the platoon density $\mathbf{D}(\mathbf{t})$ can be computed as follows:

$$\mathbf{d}(\mathbf{t}) = \frac{\mathbf{N}-\mathbf{1}}{\mathbf{l}(\mathbf{t})} \tag{2}$$

where $\mathbf{l}(\mathbf{t})$ is the platoon length derived from the aggregation of the inter-vehicle spacings for all the following vehicles of the platoon at time $\mathbf{t}$.

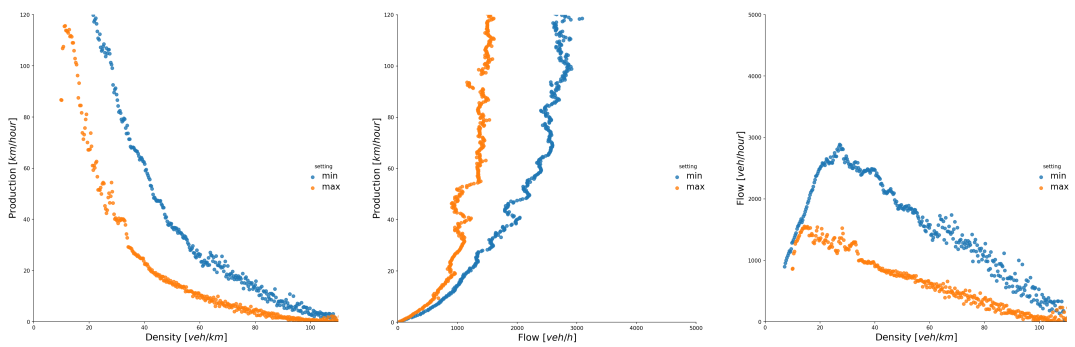
Finally, the platoon flow $\mathbf{Q}(\mathbf{t})$ at time $\mathbf{t}$ can be approximated with the following well-known relation:

$$\mathbf{q}(\mathbf{t}) = \mathbf{p}(\mathbf{t})\mathbf{d}(\mathbf{t}) \tag{3}$$

The main assumption of this model is that we can derive a meaningful relationship between the platoon density, the platoon flow and the platoon production. This relationship is called the Platoon Fundamental Diagram.

3. Results

During platoon acceleration, deceleration and equilibrium states, different behaviors arise and therefore it is interesting to be able to observe the derived PFD during each state, in order to test its general applicability. Consequently, we post-processed all available data and split the platoon trajectories in three parts, namely acceleration, deceleration and following. We obtain acceleration and deceleration parts using a local min/max algorithm on the platoon speed profile. Furthermore, we manually label the following parts, that is partial speed profiles where the vehicles follow each other in platoon formation with only slight variations on the platoon profile. Manual detection of



(a) Filtered D-P plot. **(b) Filtered Q-P plot.** **(c) Filtered D-Q plot.**

Figure 1: PFD based on aggregated instantaneous observations for minimum and maximum ACC settings.

following parts maximizes the chances of isolating stationary conditions, while this can be also performed in an automatic way for larger datasets.

Looking only on observations referring to single platoon trajectories does not allow us still to have an overview of the PFD and this is mainly because a) we have very dense measurements (at $10[Hz]$) that are not perfectly acquired, they contain noise and annotation error, and b) we have equilibrium data only around very specific speeds, also with annotation error. Since we have segmented all our signals in acceleration, deceleration and following parts, for each of these partial trajectories we keep only the average values with regard to Equations 1-3. It should be mentioned that this is only one of many possible ways to filter the observations. Even after this first filtering stage, the scatter in the PFD plots (Density-Production or D-P, Density-Flow or D-F and Flow-Production or F-P) remains significant. However, the central data tendency is more apparent.

Fortunately, a more aggressive aggregation by averaging observed density, production and flow values within density intervals reveals a very consistent behavior for ACC vehicles as shown in the Figure 1. It is essential to highlight that Figure 1 derives from aggregation of highly heterogeneous empirical observations referring to 10 worldwide empirical datasets with platoons of ACC-enabled vehicles. The measurements refer to different sampling frequencies, post-processing techniques (e.g. Kalman filtering), data acquisition equipment, number of vehicles in the platoon and intra-platoon heterogeneity.

Results show the existence of PFD, a tool for cross-comparison of any two platoons with ACC or CACC controlled vehicles, namely the Platoon Fundamental Diagram. The PFD is invariant to a high level of heterogeneity among the different experimental observations and it seems that it can consistently describe the minimum and maximum setting of commercial ACC controllers, showcasing the macroscopic impact of ACC platoons in future networks in terms of capacity, critical and jam density.

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