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When adjacent lane dependencies dominate the uncongested regime of the fundamental relationship

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A B S T R A C T

This paper presents an empirical study of the fundamental relationship between speed, v, and flow, q, (denoted vqFR) under low flow in the uncongested regime. Using new analytical techniques to extract more information from loop detector data, the vqFR from a time of day HOV lane exhibits high v that slowly drops as q increases. This curve arises after binning several million vehicles by q and only considering those bins with $q < 1200$ vph. A surprising thing happens when further binning the data by the adjacent lane speed (v2): the vqFR expands in to a fan of curves that decrease in magnitude and slope with decreasing v2. Yet each curve in the fan continues to exhibit uncongested trends, ranging from a flat curve consistent with recent editions of the Highway Capacity Manual to downward sloping curves. It is shown that this behavior was not due to the HOV operations per se, the same behavior also arises in the non-HOV period when the lane serves all vehicles and it is also observed at another facility without any HOV restrictions. This dependency on the adjacent lane is absent from most traffic flow theories.

Taking a broader view, four different factors appear to limit the speed a driver takes: (i) the roadway geometry, (ii) the posted speed limit, (iii) the vehicle ahead (car following), and (iv) traffic conditions in the adjacent lane. Whichever constraint is most binding determines the driver's speed. While the first three constraints are found in the literature, this work contributes the fourth, as per above. When the speed limit is the most binding constraint the uncongested regime of the vqFR is roughly flat with a near constant speed over a wide range of q. When the roadway geometry is the binding constraint, e.g., due to the lack of speed limits, drivers are able to travel fast enough to be sensitive to the vehicle ahead and exhibit lower v as q increases. Car following is by definition in the congested regime and thus, beyond the scope of this paper. Finally, the present work shows that as the adjacent lane moves slower, the uncongested drivers choose speeds below the speed limit and once more exhibit lower v as q increases. Although the chosen v is below the speed limit, the drivers continue to exhibit behavior consistent with the uncongested regime.

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1. Introduction

This paper presents an empirical study of the fundamental relationship (FR) between speed, v, and flow, q.[1] For brevity, we refer to this relationship as vqFR. The focus of the study is the uncongested regime of the vqFR under low flow conditions. Before proceeding, it is necessary to briefly review the conventional understanding of the vqFR and its two regimes. The vqFR is characterized as exhibiting an uncongested regime where drivers are free to choose their own speed that is roughly independent of the spacing to the leading vehicle in the same lane; thus, v is near free speed (v_f) as q increases from 0 vph. When q approaches its maximum value at capacity (q_o) then v starts to drop. Within the uncongested regime v is commonly accepted to be either constant yielding a flat curve throughout most of the uncongested regime (e.g., Fig. 1a), or v decreases as q increases yielding a negative slope in the vqFR curve throughout the uncongested regime (e.g., Fig. 1b). Then as v drops below its value at capacity drivers become constrained by their leaders and are no longer free to choose their own speed; thus, the traffic state enters the congested regime, with much lower v, and q now decreasing as v decreases (a positive slope in the vqFR plane, as evident in the lower portion of both plots in Fig. 1).

Using new analytical techniques to extract more information from loop detector data, this paper finds that the empirical vqFR from an active HOV lane exhibits high v that slowly drops as q increases. A surprising thing happens when further binning the data by the adjacent general purpose lane's speed (v2), the HOV lane's vqFR expands into a fan of curves that decrease in magnitude and slope with decreasing v2. Yet each curve in the fan continues to exhibit uncongested trends. It will be shown that this behavior was not due to the HOV operations per se. This location only has a time-of-day HOV restriction and the behavior arises in this same lane when the HOV restriction is inactive. The behavior is also observed on another freeway without any HOV restrictions at a lane drop. The process of identifying the source of this unexpected behavior provides important insights in to the factors that influence a driver's choice of speed in general, and the shape of the vqFR in particular. As discussed herein, it appears that the uncongested vqFR has an intrinsic shape and scale that are determined by various bounding factors, including the speed limit, the roadway design, and this newly found dependency on the adjacent lane speed.

This study is important because the vqFR (and other forms of the FR) are critical for much of traffic flow theory and aspects of traffic operations. A deeper understanding of the factors that influence the shape of the FR will only serve to advance those areas of traffic flow theory and traffic operations that depend on the FR. The FR dates back to Greenshields (1935), who undertook an empirical photographic study of traffic, tabulating speed, v, as a function of flow, q, in what would become known as the fundamental diagram and what the current work calls the vqFR. Greenshields also used dimensional analysis to derive $q = kv$ and project his measurements to density, k. Wardrop (1952) took a more analytical approach to the FR exhibited in the fundamental diagram, providing a rigorous theory of how speed, flow, and density relate. Starting with Lighthill and Whitham (1955) and Richards (1956) the FR became the cornerstone of most traffic flow models. The vqFR is also prevalent in practice for quantifying the level of service (LOS) on highways (see, e.g., the Highway Capacity Manual, (TRB, 2000)).

1.1. Overview

The remainder of this paper is as follows: Section 2 gives context for this work, both in terms of FR in general, and past studies of inter-lane dependences in the FR in particular. Section 3 presents the analysis, starting with a description of the data and data processing. The section then proceeds to analyze empirical data from two different freeway segments, showing the dependency on the adjacent lanes. The paper closes in Section 4 with a discussion and conclusions.

2. Background

In spite of the importance of the FR, few agree on a single shape or form to the underlying curve. Since the first empirical FR study (Greenshields, 1935) the shape and interpretation of empirical FR curves has evolved over the years. Some of the evolution is due to improvements in transportation infrastructure, the vehicle fleet, and driver capabilities. There have also been changes in data collection methods. Some papers found that the shape of the uncongested regime of the FR to be dependent on the location of data collection (e.g., Hsu and Banks, 1993; Hall et al., 1993; Carter et al., 1999), while others argue that the shape of the FR depends on whether the FR is for individual lanes or for the whole roadway (e.g., Mahabir, 1981; Allen et al., 1985; Ringert and Urbanik, 1993; Hurdle et al., 1997; Carter et al., 1999), and still other papers found a dependency on weather conditions (e.g., Ibrahim and Hall, 1994).

Ultimately, the divergent beliefs of the shape of the FR persist to this day because the empirical data used to study the relationships are quite noisy due to inhomogeneous vehicles, a range of driving behavior, measurement errors, and other factors (Coifman, 2014a). So empirical studies of the FR typically fit a curve to a scattered cloud of points and there is no universally accepted "best fit". The research community has come to accept a blurry picture as a sufficient approximation of a presumed underlying relationship. Unfortunately, this blurred picture obscures critical factors that influence traffic flow.

[1] The FR relates speed, flow, and density. The relationship is typically presented in the context of two of these three metrics; however, the third metric can easily be calculated from the other two.

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