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On macroscopic freeway merge behavior: Estimation of merge ratios using asymmetric lane flow distribution

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ABSTRACT

Data from several freeway merges reveal that, contrary to some previous findings, merge ratio can vary within a site with respect to the merge outflow and that the existing merge ratio estimates based on lane counts are not able to predict this within-site variation. Furthermore, the merge ratios estimated based on two well-known merging principles, "fair-share" and "zipper," are found to be inaccurate for merges where merging streams compete directly due to a lane drop. In light of these findings, we estimate merge ratios using lane flow distribution (LFD) to better predict between and within site variations of merge ratio. In addition, we propose a merging principle specific for merges with a single lane-drop. The model was developed to better represent observed non-uniform redistribution of merging flow not captured by the current merge ratio estimation methods and merging principles. Empirical observations show that the proposed methods are able to improve merge ratio estimates, reproduce within-site variations of merge ratio, and represent more accurately non-uniform redistribution of merging flow dependent on the merge geometry.

1. Introduction

Merges constitute important physical characteristics of freeways and have a significant impact on the performance of freeway networks, especially during congestion. At merges, drivers from conflicting traffic streams must compete to merge. Their behavior significantly affects traffic dynamics upstream and is linked to important traffic phenomena such as capacity drop (e.g., Elefteriadou et al., 1995; Cassidy and Rudjanakanoknad, 2005; Laval et al., 2005; Leclercq et al., 2011; Srivastava and Geroliminis, 2013) and traffic oscillations (Mauch and Cassidy, 2002; Ahn et al., 2010). A number of studies have attempted to describe merging traffic behavior (Papageorgiou et al., 1990; Daganzo, 1994, 1995, 1996; Lebacque, 1996; Banks, 2000; Jin and Zhang, 2003; Ni and Leonard, 2005; Chevallier and Leclercq, 2009a, 2009b). Specifically, Daganzo (1995) proposed a simple merge model where two congested traffic streams compete to merge into a single stream at a fixed ratio, referred to as a "merge ratio." For simplicity in the lack of empirical evidence, a merge ratio is assumed to be constant, though site-specific, independent of merge outflow. The model is also consistent with Papageorgiou et al. (1990) in the special case of a triangular fundamental diagram. A merge ratio is a key component to predicting congestion propagation and evaluating freeway performance in sections upstream of merges.

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Cassidy and Ahn (2005) showed using real data that the simple assumption of a constant merge ratio is, in fact, a reasonable assumption. However, observations from this study suggested that merge ratios were site-specific and appeared to depend on the merge geometry. This indicated that field measurements of merge ratio are needed at individual merges, which can be cumbersome for network applications.

Papageorgiou et al. (1990) and Ni and Leonard (2005) recognized the need for estimating the merge ratio without field data collection. They suggested using "fair share" merge ratios, which are determined in proportion to the capacities of the merging approaches, i.e., capacity ratios. However, Bar-Gera and Ahn (2010) claimed that capacity is difficult to observe in practice. Instead, they argue that the capacity ratio is intuitively similar to the "lane ratio" (based on the number of lanes of each incoming approach) since the capacity of a merging stream is mostly dictated by its number of lanes. Motivated by this premise, they conducted a macroscopic study of merge ratios using data from fifteen sites and showed that the lane ratio is a reasonable proxy for the merge ratio in the absence of field observations. Yet, significant deviations from lane ratios in some sites suggested that other factors influence merge ratios, and further analysis is needed for better accuracy.

Likewise, Daganzo (1996) discussed a merging scheme[1] where for the case of a single lane on-ramp, vehicles from the on-ramp and the shoulder lane upstream of the merge compete to merge on a one-to-one basis while the flow of the other lanes is maintained; we will refer to this premise as the "zipper" rule hereafter. However, Westland (1998) showed that this theory may be inaccurate for current geometric configuration of merges and prone to underestimating the flow of the on-ramp. He proposed to use the "geometric factor" instead, which is the ratio between the number of lanes downstream of the merge and the sum of the upstream lanes. He used the product between the geometric factor and the bottleneck capacity per lane to estimate the supply flow for each incoming lane. The method was able to accurately predict the incoming ramp flow for three merges, however this theory assumes uniform lane flow distribution (LFD), thus is ineffective for variable lane capacities.

Previous studies on LFD have found that the proportion of flow varies significantly across lanes with respect to the total freeway flow even in congestion (Amin and Banks, 2005; Carter et al., 1999; Lee and Park, 2010; Wu, 2006; Knoop et al., 2010; Duret et al., 2012; Hong and Oguchi, 2008; Hurdle et al. 1997). In the typical LFD relationship, the proportion of flow in the median lane increases as the total flow increases, while the proportion of flow in the other lanes, particularly the shoulder lane, decreases. In addition, LFD patterns were found to be variable between sites, even in sites with similar geometry (Amin and Banks, 2005; Carter et al., 1999; Lee and Park, 2010). Thus, we conjecture that the merging process can be closely related to recurrent site-specific LFD patterns near merges.

In the present study, we evaluate existing methods (the lane ratio method) and merging principles to estimate merge ratios. We identified within-site trends of merge ratio with respect to the merge outflow. We show that merge ratios are not only site-specific but can also vary within a site contrary to previous findings. These variations are attributed to merge geometry and lane-specific traffic behavior, which is not captured in the lane ratio. To better capture within-site and between-site variations of merge ratio, we formulated merge ratio based on lane flow distributions. Furthermore, we evaluated the fair-share and the zipper merging principles for several merge geometries. We found that existing merging principles do not accurately represent merging behavior at merge with a lane reduction, resulting in inaccurate merge ratio estimates. In light of this, we formulated merge ratio based on a new merging principle to capture non-uniform merging flow distribution. The proposed models based on LFD are able to (i) capture between and within site merge ratio variations more effectively, (ii) improve estimates of merge ratio, and (iii) represent non-uniform redistribution of merging flow dependent on specific merge geometries.

The remainder of this paper is organized as follows. In Section 2, the study sites and data processing method are presented. In Section 3, the estimation of merge ratio based on number of lanes is discussed. Section 4 describes the new merge ratio estimation method based on LFD. Section 5 presents the new estimation method for particular merges based on the merging principle that captures non-uniform redistribution of merging flow. In Section 6 we present the results and discussion. Conclusions are summarized in Section 7.

2. Method

2.1. Sites and data

Data from the California Performance Measurement System (PeMS) were used to conduct this study. The PeMS database provides historical traffic data for most freeways and roads in the urban areas of California. The data consist of vehicle count and occupancy (a dimensionless measure of density) aggregated in 5-min and 30-s intervals. Study sites were selected based on the following criteria necessary to compute merge ratios: (i) recurrent congestion is present at both upstream approaches and downstream of the merge (i.e. fully congested merges), (ii) either merging approach is not metered, and (iii) upstream measurement detector stations are located sufficiently close to the merge (within 0.25 miles). For (ii), we mostly considered freeway-to-freeway merges.

Two types of merges were used for this study in terms of merge geometry, which we will refer to as type 1 and type 2 merges. In type 1 merges (Fig. 1a), the sum of the number of lanes of both upstream approaches is equal to the number of lanes downstream of the merge (i.e., no lane drop). In type 2 merges (Fig. 1b), the sum of the lanes of the upstream

[1] Motivated by informal remarks made by Caltrans engineer Moskowitz to G.F. Newell.