Prediction of Merge Ratios using Lane Flow Distribution

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In this research, we (i) develop a model to estimate merge ratios using lane flow distribution and (ii) test two theoretical principles of merge ratio, the "fair-share" theory and the "zipper" rule. A merge ratio is the ratio in which vehicles from conflicting streams take turns to merge and is an important parameter for predicting congestion evolution upstream of a merge. Five study sites were used to measure merge ratios and develop the model. Our findings suggest that (i) the merge ratio model based on the lane flow distribution (LFD) performs better than the model based on the lane ratio, and (ii) the fair-share and zipper rule principles apply for different merge geometries.

1. Background

Many models have been developed to describe the macroscopic behavior of traffic at merges. Daganzo proposed a simple merge model where the merging behavior of two congested traffic streams is dictated by drivers taking turns to merge at a fixed ratio. Cassidy and Ahn (2005) verified this model empirically that merge ratios are fixed and site-specific. Ni and Leonard (2005) proposed a "fair-share" theory of merge ratio, where merge ratios are equal to capacity ratios. Assuming that all lanes have equal capacity, the capacity ratio is equal to the lane ratio under this principle. Bar-gera and Ahn (2010) performed an extensive empirical analysis of merge ratios in fifteen different sites. Results showed that the lane ratio provides a reasonable prediction of merge ratio in the absence of field data. However, noticeable residuals from the study suggested that additional factors influence merge ratios. Alternatively, traditional knowledge has suggested other principle of merge behavior referred in this manuscript as the zipper rule. This theory proposes that vehicles in the lanes adjacent to the merge take turns on a one-to-one basis, while vehicles from other lanes maintain their flow.

2. Method

Historical traffic data from the Caltrans Performance Evaluation Measurement System (PeMS) was used to select study sites and gather data. Study sites were selected based on the following criteria: (i) recurrent congestion on both merging approaches and downstream of the merge must be present, (ii) approaches are not metered, and (iii) existing detectors are located sufficiently close to the merge. A total of five study sites were selected for this research; see Table 1. Two types of merges were used for this study in terms of merge geometry. For 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. For type 2 merges (Fig. 1b) a lane drop between the upstream and downstream measurement locations exists; i.e. the sum of the lanes of the upstream approaches is greater than the number of lanes downstream of the merge.

Table 1 Summary of study sites

No.	Merge Location	Type	Lanes [a]
1	I5S I405S	1	6/3/3
2	I10E I405S	1	4/3/1
3	SR91W I5N	1	5/3/2
4	I805S SR163S	2	5/4/2
5	I405N SR22W	2	6/4/3

[a] Number of lanes order is downstream/upstream mainline/upstream merging approach.

Low-resolution (5-min) data was used to identify site-specific congestion speed thresholds and events of full congestion (i.e., congestion on all approaches). Ten congested days free of incidents and unusual weather events were selected from each site to perform high-resolution data analysis. Periods of steady states were identified using wavelet transform. Based on the identified steady-state periods, we measured merge ratio, merge outflow and LFD for each site. Figure 2 shows the relationship between the two merging inflows at the merge of Interstate 5 north into State Route 91 westbound. We can observe that the merge ratio is nearly fixed, though the measured values exhibit some variations from the merge ratio line. For this site, the measured merge ratio is 0.75, as opposed to the estimated merge ratios of 0.66 and 0.60 (based on lane ratios) under the fair-share and the zipper rule assumptions, respectively. The significant differences between the measured and estimated merge ratios underscore the need for a better estimation model. To this end, we develop a simple merge ratio model that is based on LFD.

Figure 3 illustrates the LFDs downstream of the same merge in Figure 2. Notice that they are different among lanes and vary with respect to total merge outflow. More specifically, they exhibit linear trends that are statistically significant for most of the lanes for four out of five sites. Using the site-specific linear models of LFD, we formulate merge ratios under the fair-share and the zipper rule assumptions. Specifically, let P_n and P_m denote the linear estimates of LFD of lane n and lane m for a given merge outflow respectively. Then, the merge ratio under the fair-share assumption is denoted by:

$$\alpha = \sum_{n=1}^{N} P_n \Big/ \sum_{m=1}^{M} P_m \tag{1}$$

where N is the total number of lanes on the merging approach and M is the total number of lanes on the mainline freeway approach. Similarly, the merge ratio estimate under the zipper rule assumption can be expressed as:

$$\alpha = \left(\sum_{n=1}^{N-1} P_n + \frac{1}{2} P_{adj}\right) \Big/ \left(\sum_{m=1}^{M-1} P_m + \frac{1}{2} P_s\right) \tag{2}$$

where P_{adj} is the LFD of the lane adjacent to the freeway on the merging approach and P_s is the shoulder lane. Using these formulations, predictions of merge ratio were made based on the models and they were compared to the predictions obtained using lane ratios.

3. Findings

Merge ratios were predicted using the models above for each steady-state period and compared to the predictions based on the lane ratios and the measured merge ratios. Figure 4a (fair-share) shows predicted vs. measured merge ratios with respect to the total merge outflow. The measured merge ratios exhibit a slight decreasing trend, indicating that the merge ratio varies at this site depending on the traffic condition. Evidently, this variation is not captured by the lane ratio. Furthermore, almost all measured merge ratios reside above the lane ratio line, suggesting that the lane ratio systematically underestimates the merge ratio (for this site). In contrast, predictions based on equation (1) with the LFD perform much better and follow the decreasing trend very well. We can observe similar trends in Figure 4b (zipper), though the measured values do not fall in the prediction line as nicely as in the model under the fair-share assumption.

Root-mean-squared-errors (RMSE) were calculated to measure the performance of the models. Table 2 provides a summary with the observed RMSE values. We can observe that for type

1 merges, the lowest RMSE values are obtained for the model based on LFD under the fair-share assumption. However, the results are somewhat contrary for type 2 merges, where the zipper rule applies better, though the LFD-based fair-share model performs reasonably well. Moreover, in site 4, the lane ratio under the zipper rule gives the best estimate. A possible explanation for the superior performance of the zipper rule is attributable to the fact that merging traffic directly competes due to the lane reduction. The inferior performance of the LFD-based model may be related to other factors, and an investigation in this regard is ongoing. Overall, the merge ratio model using lane flow distribution under the fair-share assumption was the most consistent in providing better estimates of merge ratio than those obtained from lane ratios. This means that, if the proportions of flow for each lane downstream of a merge are known, accurate estimates of merge ratio can be obtained with this method. The present method provides better predictions of merge ratio than lane ratios which assume equal capacity and distribution of flow across lanes.

Table 2 Summary of root-mean-squared-errors of merge ratio predictions

Site	Type	Principle	LFD Model	Lane Ratio
I5S I405S	1	Fair-Share	**0.086**	0.096
		Zipper	0.090	0.096
I10E I405S	1	Fair-Share	**0.037**	0.044
		Zipper	0.144	0.155
SR91W I5N	1	Fair-Share	**0.073**	0.102
		Zipper	0.137	0.163
I805S SR163S	2	Fair-Share	0.059	0.100
		Zipper	0.070	**0.053**
I405N SR22W	2	Fair-Share	0.083	0.087
		Zipper	**0.063**	0.065

References

Bar-gera, H., Ahn, S., 2010. Empirical macroscopic evaluation of freeway merge-ratios. Transportation Research Part C: Emerging Technologies, Vol. 18, No. 4, pp. 457-470.

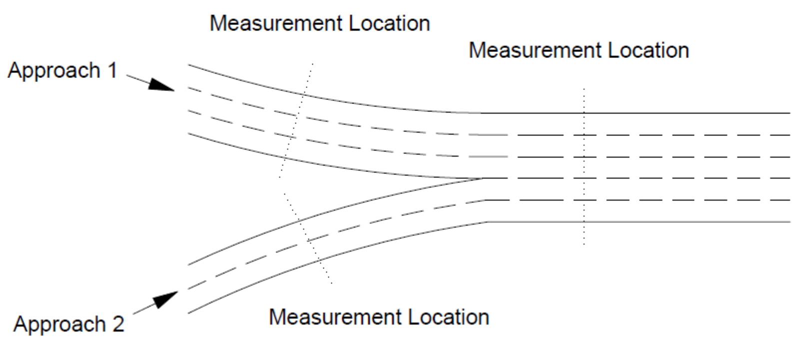
Cassidy, M., Ahn, S., 2005. Driver turn-taking behavior in congested freeway merges. Transportation Research Record: Journal of the Transportation Research Board, Vol. 1934, pp.140-147.

Daganzo, C. F., 1995. The cell transmission model, part II: network traffic. Transportation Research Part B, Vol. 29, No. 2, pp. 79-93.

Ni, D., Leonard, J. D., 2005. A simplified kinematic wave model at a merge bottleneck. Applied Mathematical Modelling, Vol. 29, No. 11, pp. 1054-1072.

Figures

(a)



(b)

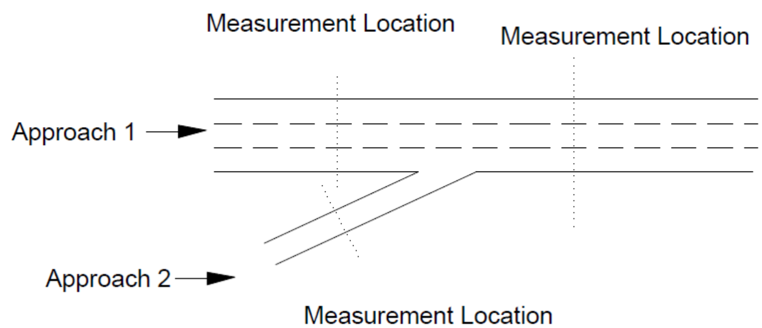


Figure 1 Merge schematics, (a) type 1 merge (b) type 2 merge

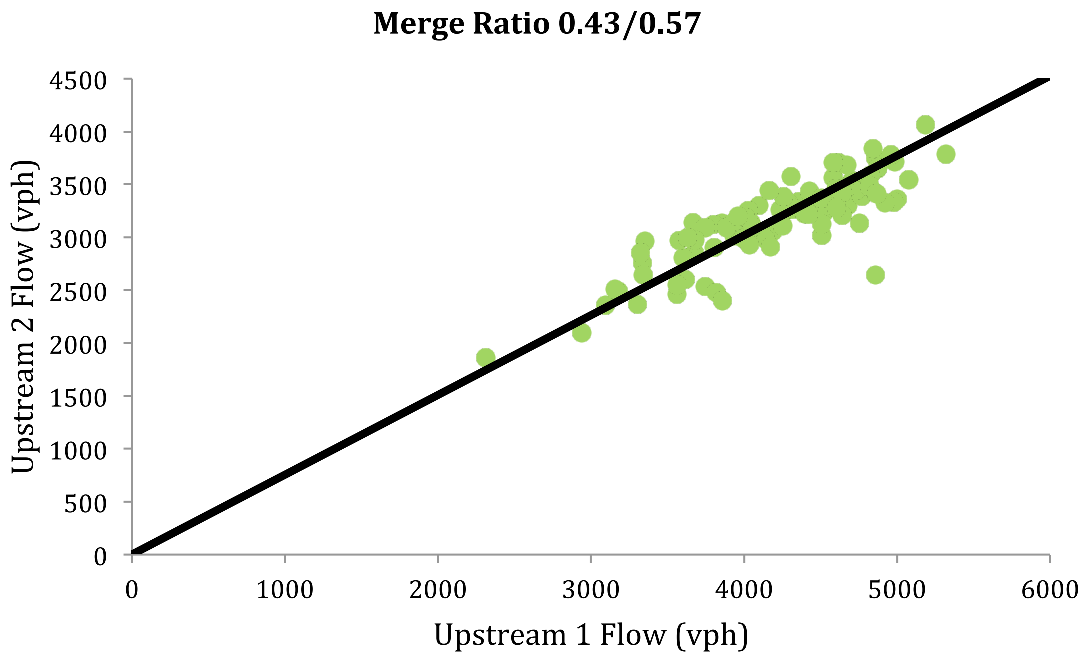


Figure 2 Relationship between upstream flows of the merge of Interstate 5 north into State Route 91 westbound (SR91W I5N)

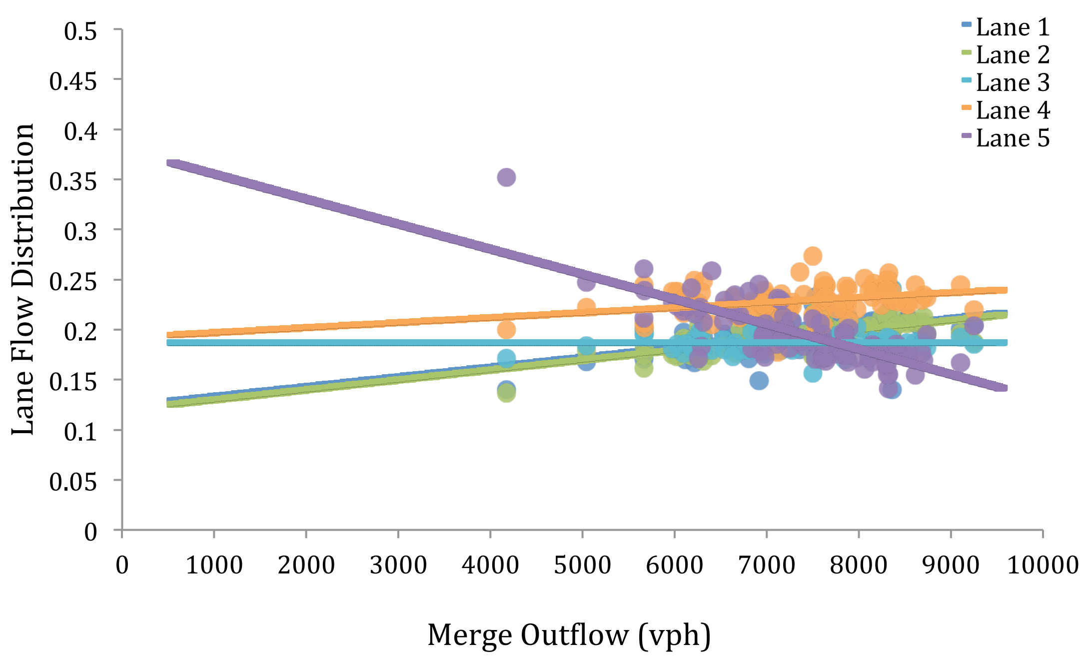
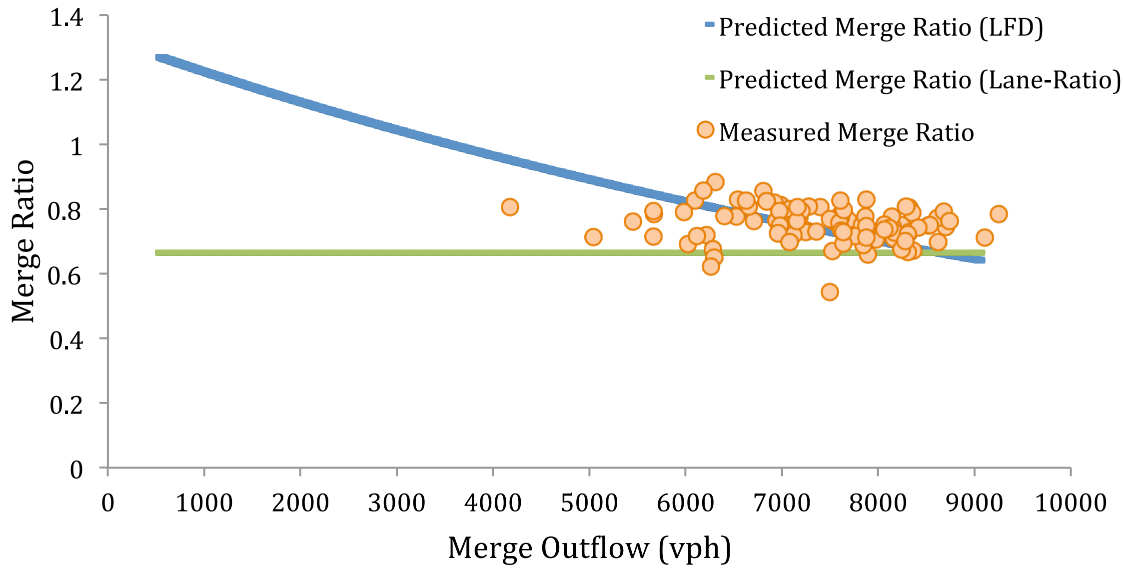


Figure 3 Lane flow distribution and predictions based on linear regressions models (SR91W I5N) where lane 1 represents the median lane and lane 5 represents the shoulder lane

(a)



(b)

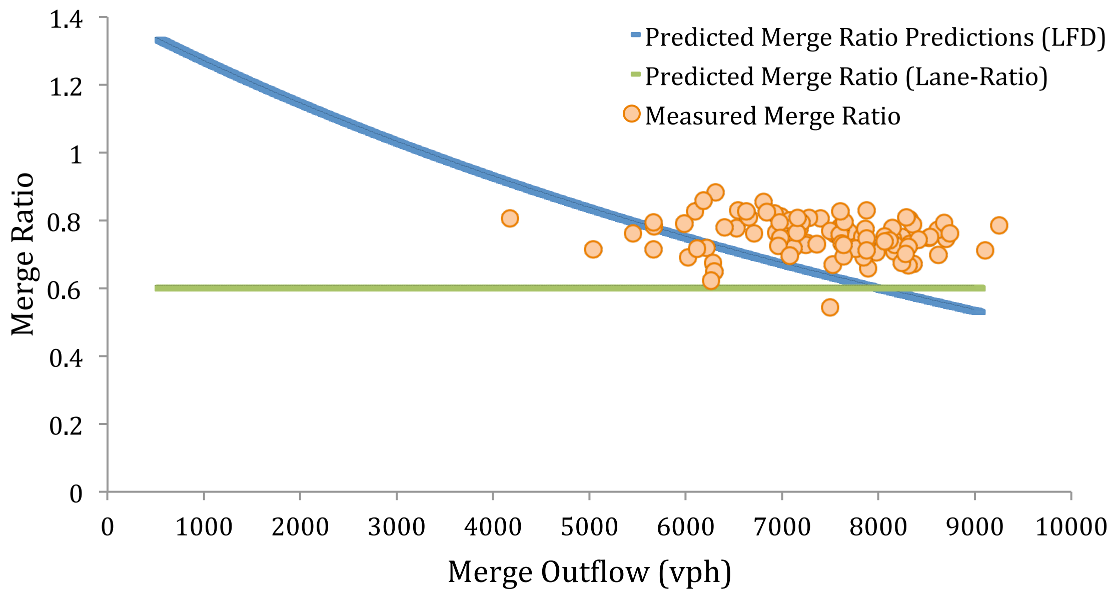


Figure 4 Predictions of merge ratio (SR91W I5N) based on the models (a) fair-share theory (b) zipper rule