Impacts of lane changes at merge bottlenecks: a theory and strategies to maximize capacity*

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Abstract. Recent empirical observations at freeway merge bottlenecks have revealed: (i) a drop in the bottleneck discharge rate when queues form upstream, (ii) an increase in lane-changing maneuvers simultaneous with this "capacity drop", and (iii) a reversal of the drop when the ramp is metered.

This paper shows that a simple vehicle lane changing theory, which has been shown to explain related phenomena at lane-drops and moving bottlenecks, also explains the new phenomena at merges. In this theory, lane-changing vehicles are modeled as discrete particles endowed with realistic accelerations, and are embedded in a multilane stream where each lane obeys the kinematic wave model. This theory is parsimonious: only one of its four parameters has to be calibrated by running the model.

Our simulations show that the theory predicts surprisingly well the cumulative flows at all locations, the vehicle trip times, the number of lane-changing maneuvers, the capacity drop, its recovery upon metering, and the distribution of these measures across lanes and over time. Applications are discussed.

1 Introduction

The kinematic wave (KW) model [1,2], when applied with a triangular fundamental diagram (KWT) [3], is arguably the simplest means to explain basic traffic features, such as the spatial extent of queues and average vehicle densities within these queues [4–9]. But more complex traffic features, such as the capacity drop [10–14], hysteresis [15], the capacity of moving bottlenecks [16] and stop-and-go waves [17–21,5] cannot be explained with such a simple model.

Many of these features, however, are explained by a multilane hybrid (MH) theory that combines the KW model with discrete lane changes treated as moving bottlenecks [22]. This paper shows that the theory also explains traffic behavior at merges. Section 2 describes the key concepts of the theory in [22] and the proposed treatment of merges. Section 3 tests the model and section 4 discusses its results.

2 Parameters of the Multilane Hybrid model with merges

The multilane hybrid (MH) model in [22] treats each lane as a KWT traffic stream, interrupted by lane-changing vehicles. The KWT model has three parameters that can be measured by direct observation: a "free-flow" speed, u

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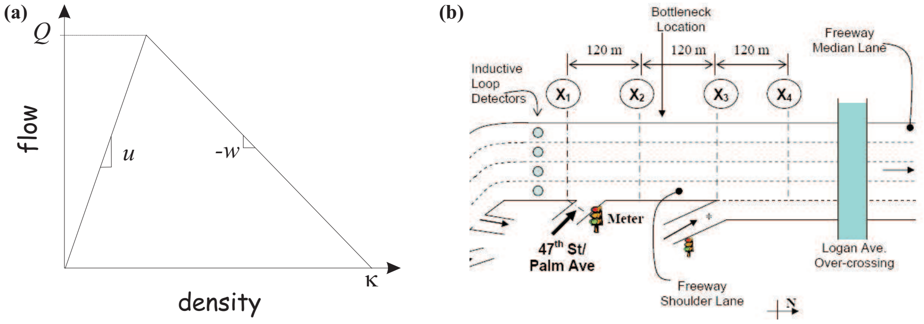

Fig. 1. (a) Triangular fundamental diagrams; (b) site description (taken from [23]).

(km/hr), a wave speed, w (km/hr), and a "jam density", κ (veh/km). One can also define a "capacity", Q (veh/hr), related to the previous three parameters by: $Q/u + Q/w = \kappa$; see Fig. 1a. Typical values (used on all our tests) are: $u = 112.7$ km/h (70 mph), $w = 22.5$ km/h (14 mph) and $\kappa = 139.7$ veh/km (225 veh/mile). Therefore, $Q = 2,625$ veh/hr.

Lane-changing vehicles are treated in the MH model as discrete particles with variable speeds and accelerations (v, a), subject to upper bounds: $v \leq v_{max}; a \leq a_{max}$. These bounds are parameters of the model, but they can be chosen without running the model, simply by analyzing the vehicle fleet. For all of our tests we chose features of an average car on level terrain: $v_{max} = 123.8$ km/hr and $a_{max} = 3.4(1 - v/v_{max})$ m/s^2.

Lane changes are assumed to be triggered by speed differences between adjacent lanes, and drivers' desire for travelling faster. This is modeled by a probability rate for lane changing (probability per unit time), π, which defines the behavior of a driver experiencing a speed deficit, $\Delta v \geq 0$, relative to a neighboring lane. The behavioral relationship is assumed it to be of the form: $\pi = \Delta v/(u\tau)$, where τ is a behavioral parameter with units of time. This is the only parameter that is estimated by running the model.

Given u, w, κ, τ, and the upstream traffic demand, the model can be simulated in discrete time by inspecting the system at intervals Δt (sec); see [22]. It predicts the flow and accumulations by lane at any desired set of locations and the number of lane changes between every pair of adjacent lanes. As explained in [22], the model reproduces the capacity drop at lane-drops because lane changers with bounded accelerations introduce voids in the traffic stream, which pass through a bottleneck to the detriment of its discharge rate.

The on-ramp was modeled as an additional freeway lane with the same abovementioned KWT parameters. Since our site did not have an acceleration lane, we neglected its length; ie, lane changes to/from the freeway can only take place at a point. Given that several on-ramp vehicles may enter the freeway at the same time, an additional condition is imposed at the boundary with the freeway. At this boundary, the on-ramp capacity is expanded by 40 %. Notice that this

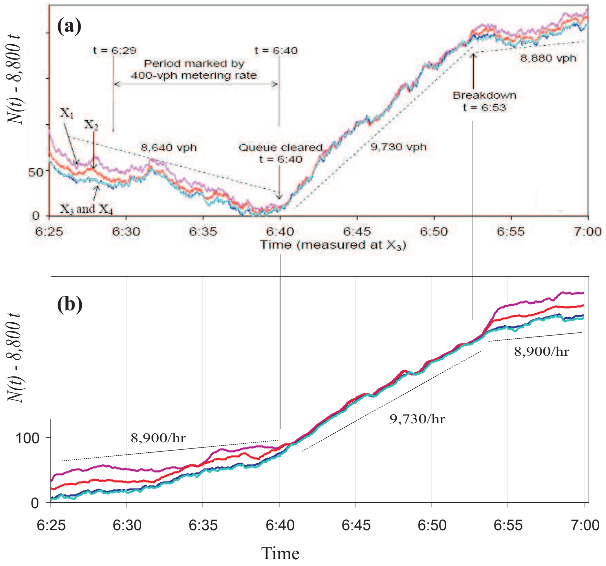

Fig. 2. Oblique queueing diagrams on October 15st: (a) measured (taken from [23]); (b) simulated.

expanded capacity does not induce on-ramp inflows greater than Q; it merely implements the boundary condition for merges proposed in [25] by increasing the priority for entering traffic to the levels observed in [24].

3 Tests

In this section we show how the MH model replicates the empirical observations at an on-ramp merge in [23]. We describe these observations first.

3.1 Field measurements

The experiments in [23] are the first to reveal some of the mechanisms that lead to lower bottleneck discharge rate after queues formed upstream. The site is a stretch of northbound Freeway 805 in San Diego, California; see Fig. 1b. The merge formed by the metered on-ramp at 47th St/Palm Ave on-ramp, is a recurrent active bottleneck. The experiments were conducted during ten morning rush periods in summer and fall 2003. Capacity drops and recoveries due to select ramp metering strategies were observed. The rush periods of October 15th and October 21st were selected for analysis in this paper.

Detailed traffic data were manually extracted from videos. The empirical data for October 15th are presented in Figs. 2a and 3a-b, while the data for October 21st correspond to Figs. 4a and 5a-b. These figures display the following time series:

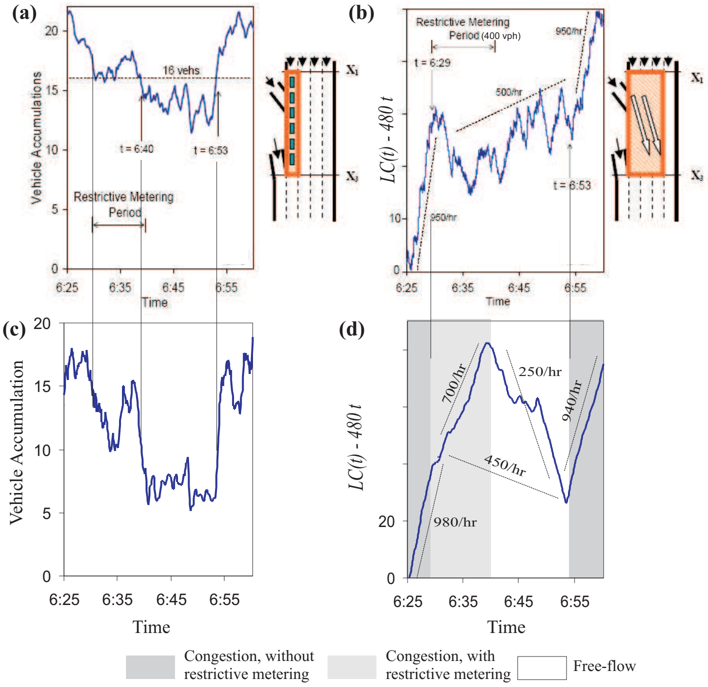

Fig. 3. Time series of accumulations and lane-changing: (a) measured shoulder lane accumulation on October 15st (taken from [23]); (b) measured lane-changing flows on October 15st (taken from [23]); (c) measured shoulder lane accumulation; (d) measured lane-changing flows.

- Oblique queueing diagrams: a transformation of cumulative vehicle count vs time, $N(t)$, measured at the four locations labelled X_1 through X_4 in Fig. 1b; see [26]. Notice that to guarantee flow conservation ramp inflows were added to the counts upstream of the bottleneck.
- Vehicle accumulations: the number of vehicles in the shoulder lane (only) between locations X_1 and X_3, as per the illustration directly to the right of Fig. 3a. These accumulations were sampled from video every 5 sec and the curve presents the averages of these counts over 1-min intervals.
- Oblique cumulative lane changes, $LC(t)$: this plot corresponds to the commutative number of vehicle lane changes between X_1 and X_3 on an oblique coordinate system to amplify the variations in the lane changing activity. Only lane changes leaving the two rightmost lanes were considered; see schematic to the right of Fig. 3b.

Examination of these figures (2a, 3a-b, 4a and 5a-b) reveals that (i) the capacity drop occurs simultaneously with an increase in lane-changing counts and shoulder lane vehicle accumulation, and that (ii) controlling the ramp-metering

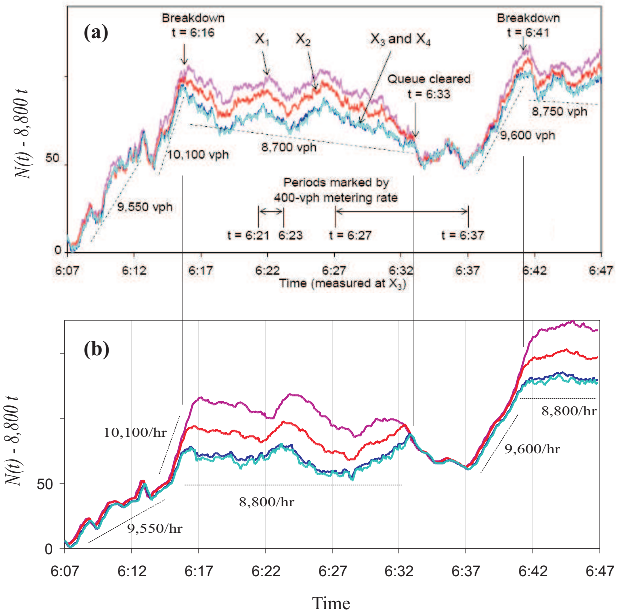

Fig. 4. Oblique queueing diagrams on October 21st: (a) measured (taken from [23]); (b)simulated.

rate could mitigate this lane changing and accumulation, so that high merge capacities could be restored.

3.2 Simulation results

The input data for the simulations consisted of the lane-specific traffic demands measured in 30-sec intervals at the loop-detector located upstream of X_1 (see Fig. 1b[1]), and the demand on the on-ramp–taken from [23]. The behavioral parameter $\tau = 4$ sec was found to replicate the number of lane changes during congested periods and was used throughout. We also chose Δt= 0.6 sec, but any small value for the time increment would work similarly.

Simulation results are shown below the corresponding empirical charts on Figs. 2 to 5. Vertical solid lines connecting the empirical and simulated charts have been added to facilitate comparisons.

Examination of Figs. 2 and 4 reveals that the simulation accurately predicts the cumulative count curves at all locations. In all cases, the theory predicts bottleneck activation times to within 30 seconds of the observed times. Predicted bottleneck discharge rates are within 3% of those observed.

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[1] Notice that when a queue reached this detector it no longer measures demand but the bottleneck discharge rate. When this happened we extrapolated the last demand value into future time steps.

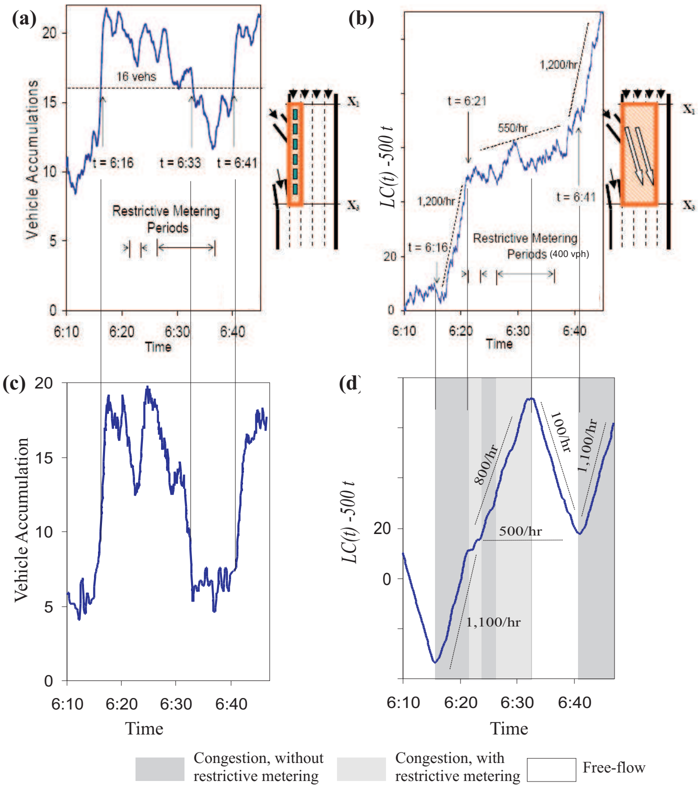

Fig. 5. Time series of accumulations and lane-changing: (a) measured shoulder lane accumulation on October 21st (taken from [23]); (b) measured lane-changing flows on October 21st (taken from [23]); (c) measured shoulder lane accumulation; (d) measured lane-changing flows.

Although discrepancies exist between the predicted and observed curves of shoulder-lane accumulations and cumulative lane changes (Figs. 3 and 5), key features of these microscopic measures are reproduced by the theory. In particular, the predicted time series of shoulder lane accumulations exhibit similar shapes to those observed, though the theory underpredicts the numeric values. Predicted lane-changing maneuvers match those observed during congested times outside of restrictive metering periods (this traffic regime is color-coded dark gray in Figs. 3d and 5d). Prediction errors arise for the other regimes; these being congestion during restrictive metering periods (light gray in the figures) and free-flow conditions (white). Notably, however, the total number of lane-changing maneuvers predicted over these two regimes combined closely match observed numbers. The observed times of regime change are also closely matched by the theory.

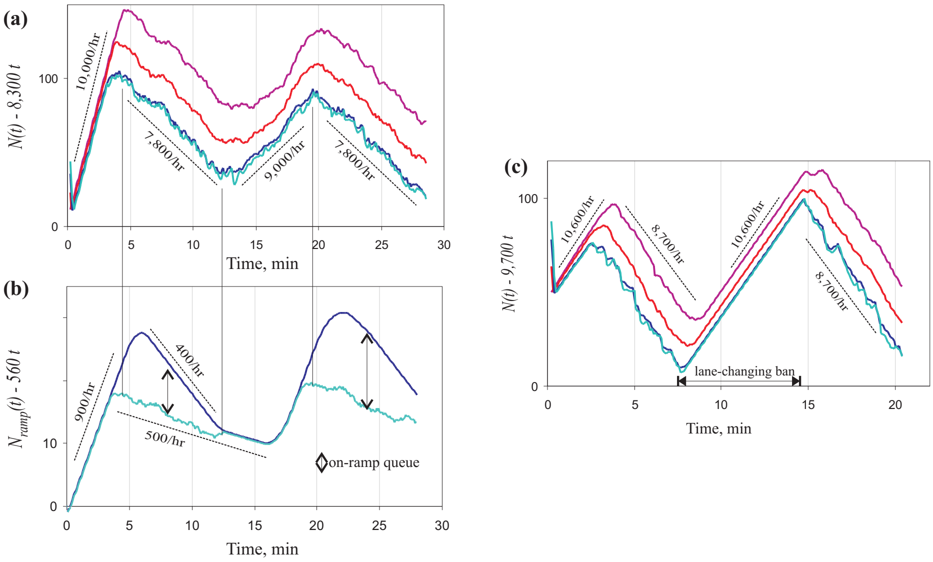

Fig. 6. Simulation of the effects of two control schemes: (a) oblique queueing diagrams on the freeway and (b) on the on-ramp; (c) oblique queueing diagrams on the freeway with a temporary lane-changing ban.

4 Discussion

The generally good fit between theory and observation– particularly on the important aggregate measures–is encouraging, given the paucity of model parameters. A perfect match between theory and observation should not be expected at the microscopic level given (i) that observations vary significantly from day to day; and (ii) that our behavioral assumption was the simplest possible. In fact we find it surprising that a single-parameter model could reproduce so much detail.

With this in mind, we now use the model to assess the capacity enhancements generated by two control schemes: one focusing on on-ramp flow, the other on freeway lane-changing maneuvers. Predictions for the first of these solutions are displayed in Fig. 6a-b. These were produced for a constant freeway demand and for on-ramp demands that cause the ramp queue to grow slowly and then recede. Note how three capacities arise: a full capacity of 10,000 veh/hr that arises with no queues on the freeway nor on the on-ramp; an intermediate capacity of 9,000 veh/hr with a queue only on the freeway; and a low capacity of 7,800 veh/hr with queues both on the freeway and the on-ramp. The latter two capacities correspond to roughly 10 and 20% of the full capacity, and are consistent with the range of capacity drops reported in the literature. Notice that both drops occur when the on-ramp input flows are 500 veh/hr in both cases. Therefore, the 1,200 veh/hr difference in discharge flow from the merge most likely occurs because queued on-ramp vehicles enter the freeway at low speeds. Thus, the model predicts that preventing on-ramp queues is of critical importance. Note too that varying traffic conditions on the on-ramp induce oscillations in the discharge rate and can contribute to oscillations in the freeway queue.

Predictions for the second control scheme are shown in Fig. 6c. These prediction are made for the same site under constant freeway and on-ramp demands, but now a lane-changing ban is imposed on freeway traffic in $t \in [7, 14]$ min. It is clear how full capacity is restored during the period of no lane-changing activity. Notice that full recovery was possible because no queues formed on the on-ramp. Had there been a ramp queue, merge capacity would have been partially recovered, as per our preceding results. These topics are currently under further investigation by the authors.

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