PASSING RATES TO MEASURE RELAXATION AND IMPACT OF LANE-CHANGING IN CONGESTION

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ABSTRACT

Passing rate measurements of backward-moving kinematic waves in congestion are applied to quantify two traffic features; a relaxation phenomenon of vehicle lane-changing and impact of lane-changing in traffic streams after the relaxation process is complete. The relaxation phenomenon occurs when either a lane-changer or its immediate follower accepts a short spacing upon insertion and gradually resumes a larger spacing. A simple existing model describes this process with few observable parameters. In this study the existing model is reformulated to estimate its parameter using passing rate measurements. Calibration results based on vehicle trajectories from two freeway locations indicate that the revised relaxation model matches the observation well. The results also indicate that the relaxation occurs in about 15 seconds and that the shoulder lane exhibits a longer relaxation duration. The passing rate measurements were also employed to quantify the post-relaxation impact of multiple lane changing maneuvers within a platoon of 10 or more vehicles in queued traffic stream. The analysis of the same datasets shows that lane-changing activities do not induce a long-term change in traffic states; traffic streams are perturbed temporarily by lane-changing maneuvers but return to the initial states after relaxations.

Keywords: passing rate, lane-changing maneuvers, relaxation

INTRODUCTION

Recent experimental studies have shown that lane-changing (LC) is a primary causal factor for several important traffic phenomena. Cassidy and Rudjanakanoknad (2005) show that near a merge bottleneck, systematic lane-change maneuvers from a freeway shoulder lane to faster left lanes cause traffic breakdown and decrease the overall bottleneck discharge rate. Similar findings have been reported by other studies (Elefteriadou et al., 1995; Banks, 1999; Cassidy and Bertini, 1999; Bertini and Leal, 2005), which gave rise to a variety of bottleneck detection methods (e.g., Chen et. al, 2004), models for sensor locations to identify freeway bottlenecks (Liu and Danczyk, 2009), and various traffic pattern analysis for traffic forecasting (Jiang and Adeli, 2004; Jiang and Adeli, 2005; Vlahogianni et al., 2007; 2008; Xie et al, 2007; Yang and Recker, 2008). Ahn and Cassidy (2007) show that LC maneuvers are a primary cause for the formations and growths of freeway stop-and-go oscillations in congestion. These studies, however, illustrate the causal relationship in a qualitative manner (Ahn and Cassidy, 2007) or at a macroscopic scale by correlating LC rates to the occurrence of capacity drop (Cassidy and Rudjanakanoknad, 2005). Coifman et al. (2006) explicitly studied the impact of LC at a microscopic level by relating the number of entering and exiting vehicles to the delay using the method of Coifman and Cassidy (2002). The results show that a delay caused by an entering vehicle is larger than a saving in delay by an exiting vehicle. However, transient states resulting from LC maneuvers were not incorporated in their method to measure delay.

Empirical observations of multilane facilities show that the LC relaxation (a transient state upon an LC maneuver) occurs as either a lane-changer or the immediate follower in the target lane accepts a short spacing upon a LC maneuver in congestion and then "relaxes" to resume a larger spacing (Smith, 1985; Leclercq et al., 2007; Ma and Ahn 2008). The LC relaxation is a microscopic phenomenon but has several known macroscopic consequences: (i) Leclercq et al. (2007) shows that it affects steady-states and the measurement of a fundamental diagram in congestion; (ii) Laval and Leclercq (2008) explain that a vehicle under relaxation acts as a moving bottleneck in congestion and determines the trajectories of followers; (iii) Ahn and Cassidy (2007) show that lane-change maneuvers can trigger traffic oscillations whose amplitude may depend on the relaxation process.

Laval and Leclercq (2008) have developed a simple model with few observable parameters to describe the LC relaxation phenomenon. However, this model involves parameters that are neither intuitive nor easy to calibrate. The objective of the present study is to (i) propose an alternative formulation of the relaxation model by Laval and Leclercq, (ii) calibrate the revised model using vehicle trajectory data, and (iii) evaluate the post-relaxation impact of LC in congested traffic. The revised relaxation model involves passing rate, which is a variable consistent with Daganzo's variational theory of kinematic waves (Daganzo, 2005) and facilitates more straightforward calibrations. The post-relaxation impact of LC is also measured using the passing rate.

The remainder of the manuscript is organized as follows. Section 2 summarizes the existing literature related to existing LC models and the LC relaxation model by Laval and Leclercq

(2008). Section 3 describes how passing rates along kinematic waves are measured. Section 4 presents the reformulation of the LC relaxation model, and section 5 discusses the calibrations of the parameters of the revised model. Section 6 provides the application of the passing rate measurements in quantifying the post-relaxation impact of LC in congested traffic. Section 7 offers discussion of the findings and concluding remarks.

BACKGROUND

Lane-changing Models

Modeling LC processes and predicting their roles in traffic dynamics involve three primary elements: LC decision, relaxation upon maneuvers, and impacts on traffic upstream. The decision process, whether to change lanes, is mostly realized as LC rates given traffic conditions. The LC relaxation occurs when a lane-changer or its immediate follower accepts a smaller spacing than the spacing in absence of LC and then gradually recovers a larger spacing. Finally, this relaxation process, along with the behavior of the followers in the initial and target lanes, governs the evolution of traffic upstream.

The existing literature provides a wealth of research on the decision process, particularly in the framework of microscopic simulations coupled with car-following models (e.g., Chandler et al., 1958; Gipps, 1981; Kesting and Treiber, 2008). Gipps (1986) provided a framework to model the decision process of LC, which consists of three primary steps to assess necessity, desirability and feasibility of an individual LC maneuver. Many microscopic LC models emerged based on this framework (Wu et al., 2000; Toledo et al., 2005; Hidas, 2005; Choudhury et al., 2007; Kesting et al., 2007). These models typically involve a large number of behavioral parameters that cannot be easily measured from field data. This makes calibration and validation of these models quite challenging and increases a risk of over-calibrating the model as the number of parameters increases.

Laval and Daganzo (2006) developed a parsimonious model in the framework of the kinematic wave (KW) model of Lighthill and Whitham (1955) and Richards (1956). Unlike the earlier extensions of the KW model (e.g. Michalopoulos et al., 1984; Daganzo, 1997; 2002a; 2002b), this model treats LC maneuvers as particles with realistic properties such as bounded accelerations. Each lane is treated as a separate KW stream with a lane-changer as a moving bottleneck that blocks the entire lane. The LC rate is determined based on a speed difference of neighboring lanes. The model involves four physically meaningful parameters and is able to reproduce the reduction in bottleneck discharge rate and the capacity of a moving bottleneck. The model predictions were verified empirically using macroscopic observations (Laval et al., 2005). However, LC relaxation was not incorporated in the model due to the macroscopic nature in its formulation.

LC Relaxation Model: Laval and Leclercq (2008)

Smith (1985) has first observed the LC relaxation phenomenon, but it received little attention until Laval and Leclercq (2008) proposed a model (the LL model hereafter) to describe the phenomenon. Laval and Leclercq introduced an application of Laval and Daganzo (2006) in a microscopic framework by incorporating the car-following rule by Daganzo (2006), which is a discrete-time formulation of Newell (2002), and treating individual LC maneuvers (or their new leaders) as moving bottlenecks. The model also incorporates the LC relaxation process with several physical parameters.

In the LL model, a lane changer initially accepts a small spacing after a maneuver, representing a non-equilibrium state (i.e., a deviation from the assumed car-following rule of Daganzo (2006)), and then relaxes to return to the equilibrium. Note that a small spacing can also occur between the lane-changer and the immediate follower in the target lane. Thus, the follower can also exhibit a relaxation phenomenon.

Laval and Leclercq (2008) have proposed the following formulation to describe the relaxation process followed by an LC maneuver using macroscopic variables in a microscopic framework.

$$\Delta N^{i+1}(t) = \Delta N^{i+1}(0) + \frac{\varepsilon w \kappa}{\beta} \ln \left[1 + \frac{\beta t}{v^i(0) + w} \right] \quad (1)$$

where $\Delta N^{i+1}(t)$ is the difference in cumulative number of vehicles between vehicle *i* and vehicle *i+1* (which can be a lane-changer or the immediate follower) at time *t*; κ is the jam density; β is a constant acceleration rate of the lead vehicle; ε corresponds to the speed difference vehicle *i+1* is willing to accept during the relaxation process. One might expect that $\Delta N^{i+1}(t)$ is always one. However, in Laval and Leclercq (2008), vehicle *i+1* obeys the microscopic moving bottleneck model with a vehicle *i* treated as a boundary condition without physical dimension. $\Delta N^{i+1}(t) = 1$ if vehicle *i+1* is in equilibrium but $\Delta N^{i+1}(t) < 1$ otherwise. This description allows a proper definition of the equilibrium and non-equilibrium states of car-following.

In Leclercq et al. (2007) the LL model was verified using individual data from the Next Generation Simulation (NGSIM) program (NGSIM, 2010). This was done at a macroscopic level by examining the relaxation paths on a flow-density plane from non-equilibrium (near insertion location) to equilibrium zones. The model was also verified at a microscopic level by calibrating individually the parameters of the lane changer and of the immediate follower when the spacing after a lane change exhibits a non-equilibrium value.

Chevallier and Leclercq (2008) developed a new microscopic framework for (congested) merges by incorporating vehicle relaxation process of the LL model into Newell's car-following model (Newell, 2002) and incorporating a fixed merge ratio into an insertion

decision algorithm. This model has few parameters that are observable in the field and was partially validated at two roundabouts.

The present study proposes an alternative formulation of the LL model using a different variable, passing rate, for the following reasons: (i) the passing rate is continuous in time and space and thus more intuitive than $\Delta N^{i+1}(t)$; (ii) it allows for more efficient calibrations since it can be easily measured from trajectory data; (iii) the passing rate is used for the solution methods of the variational formulation of kinematic waves (Daganzo, 2005) and the estimation of a fundamental diagram (Chiabaut et al., 2009), thereby establishing a connection to the macroscopic models. The calibration method by Leclercq et al. (2007) requires pre-calibration of a parameter, jam density, which is not straightforward to measure. Our method includes pre-calibration parameters, such as average vehicle speed and a backward moving wave speed in congestion, which are relatively easy to measure from field data. Of note, these pre-calibration parameters have already been calibrated for the NGSIM dataset (Chiabaut et al., 2009). Finally, in the previous calibration method, the performance was measured as the difference between the observed trajectory and the simulated trajectory (with the relaxation model). Our method allows one to observe the dynamics of a relaxation process over time using passing rates, which is more consistent with the KW model and its simplified version (Newell, 1993).

Of note, Chiabaut et al. (2009) developed a method to estimate the shape of a fundamental diagram using passing rate measurements. They analyzed the vehicle trajectories that were collected as part of the NGSIM program (2010) and found that 1) the passing rates in absence of LC maneuvers are constant independent of traffic states, and 2) the congested branch of the fundamental diagram can be assumed linear. Their findings support Newell's car-following theory and simplified kinematic wave theory (Newell, 1993).

PASSING RATE MEASUREMENT

Car-following behavior in absence of LC is assumed to follow Newell (2002) as supported by recent empirical studies (Ahn et al., 2004; Wang and Coifman, 2008; Duret et al., 2008; Chiabaut et al., 2009). Newell's model involves few parameters and uses logic that is different from conventional car-following models such as stimulus-response based models (e.g., Chandler et al., 1957). In this theory, a driver selects his spacing for a given speed in such a way that his trajectory replicates his leader's with a displacement in time and space, respectively, under a congested regime. In Figure 1(a), τ^i and d^i correspond to the displacements in time and space for vehicle i in response to the leader's speed change from v to v'. Thus, the kinematic wave propagates from vehicles i-1 to i at the speed of $w^i = d^i /\tau^i$, and the quantity $r^i = 1/\tau^i$ represents the passing rate for vehicle i, the rate at which the flow passes through the kinematic wave. The model assumes constant wave speed w^i and passing rate r^i (i.e. d^i and τ^i) independent of speeds for each individual vehicle. This implies that the relationship between spacing and speed for a vehicle is linear (since spacing of vehicle i, $s^i = d^i + \tau^i v$) as illustrated in Figure 1(b). Finally, w^i and r^i are assumed to come

from a joint distribution such that a disturbance propagates from one vehicle to another as a random walk (Newell 2002).

At the macroscopic level, this simple car-following model corresponds to triangular flow-density relations as shown in Figure 1(c). The slope of the congested branch corresponds to the maximum kinematic wave speed w and its intercept to the flow axis represents the maximum passing rate r. As noted in Chiabaut et al. (2008), w and r are estimated as the harmonic means of w^j's and r^j's, respectively, across vehicles. Moreover, as the number of sampled vehicles increases, the estimated means converge to w and r.
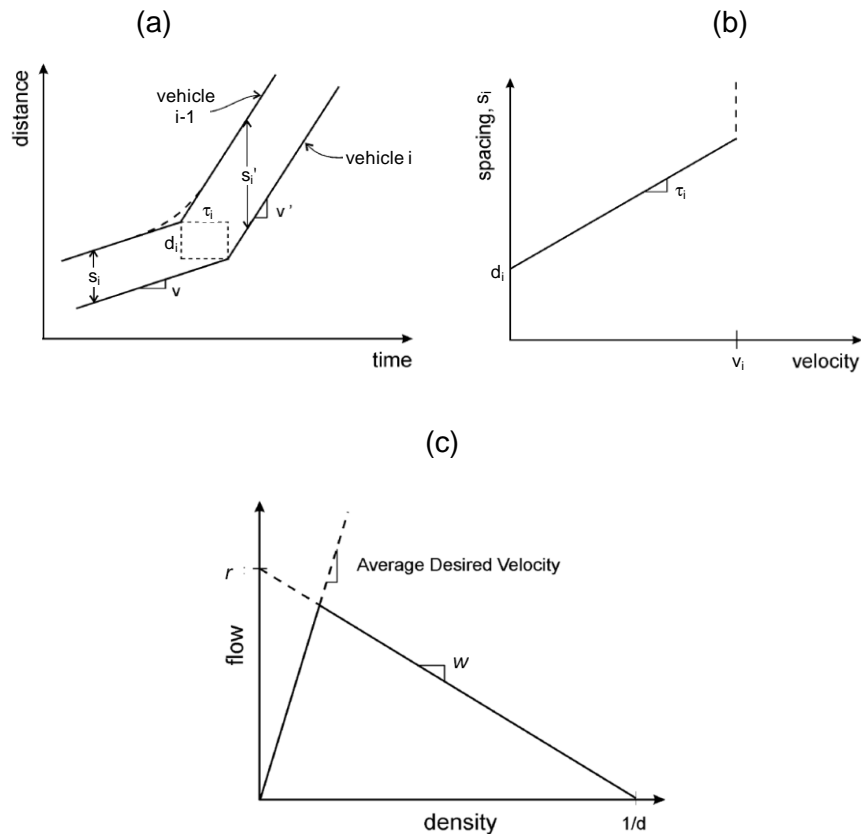
Figure 1 – Newell's car-following theory

(a) A hypothetical pair of vehicle trajectories (adopted from Newell (2002))

(b) Speed-spacing relationship for vehicle *i* (adopted from Newell (2002))

(c) Flow-density relationship (adopted from Ahn and Cassidy (2004))

REFORMULATION OF THE LL MODEL USING PASSING RATE

In this section, we derive an alternative formulation (strictly equivalent to the model by Laval and Leclercq[1]) in terms of passing rate since working with $\Delta N^{i+1}(t)$ is not convenient for calibration; the physical measurement of $\Delta N^{i+1}(t)$ using vehicle trajectories when $\Delta N^{i+1}(t) < 1$ is not straightforward (nor intuitive) since the number of vehicles is discrete. Chiabaut et al. (2009) have proposed a new measurement of car-following equilibrium states using passing rates, which are effective for measuring the transient state during relaxation. The alternative formulation using passing rate can be implemented straightforwardly to calibrate parameters, such as *β* and ε, given vehicle trajectories.
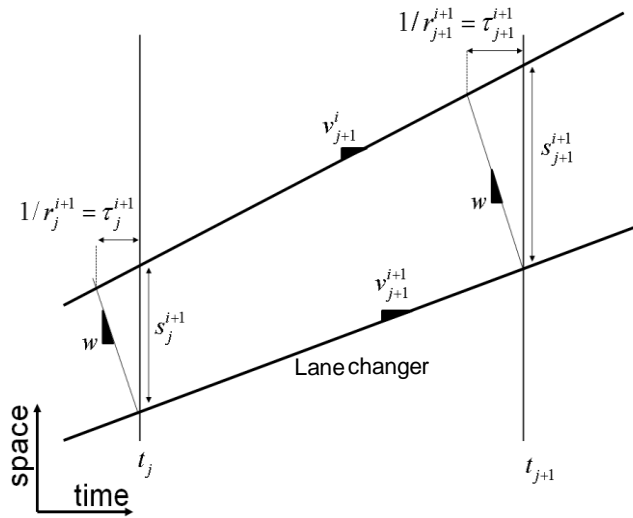

Figure 2 – Measurement of passing rates during the relaxation process of a lane changer

From Figure 2, the following relationships can be derived.

$$s_j^{i+1} = (w + v_{j+1}^i) \cdot \tau_j^{i+1} \tag{2a}$$

$$s_{j+1}^{i+1} = (w + v_{j+1}^i) \cdot \tau_{j+1}^{i+1} \tag{2b}$$

The superscript and subscript indices, *i* and *j*, refer to the vehicle number and the time step, respectively, and all variables and parameters are previously defined (see Section 3). Subtracting (2a) from (2b) gives

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[1] Our reformulation is strictly consistent with the original LL model since our derivation follows the same underlying principles (e.g., the use of the car-following model by Newell (2002) and its time-discrete expression by Daganzo, 2006).

$$s_{j+1}^{i+1} - s_j^{i+1} = (w + v_{j+1}^i) \cdot \tau_{j+1}^{i+1} - \tau_j^{i+1} \qquad (3)$$

The left-hand-side of (3) can also be expressed in terms of the speed difference between the leader and the follower at time step *j+1* and the time increment, Δt (= $t_{j+1} - t_j$); i.e.,

$$s_{j+1}^{i+1} - s_j^{i+1} = (v_{j+1}^i - v_{j+1}^{i+1}) \cdot \Delta t \qquad (4)$$

Then, combining (3) and (4) yields

$$\frac{\tau_{j+1}^{i+1} - \tau_j^{i+1}}{\Delta t} = \frac{(v_{j+1}^i - v_{j+1}^{i+1})}{(w + v_{j+1}^i)} \qquad (5)$$

Laval and Leclercq (2008) considers the lead vehicle as a moving bottleneck and introduces the follower's desired speed, $\tilde{v}_{j+1}^{i+1}$, which is expressed as

$$\tilde{v}_{j+1}^{i+1} = \underbrace{v_{j+1}^i \cdot (1 - \frac{\tau_{j+1}^{i+1}}{\tau_j^{i+1}}) + v_j^i \cdot \frac{\tau_{j+1}^{i+1}}{\tau_j^{i+1}}}_{MB-speed} - \varepsilon \qquad (6)$$

Substituting (6) into (5) yields

$$\frac{\tau_{j+1}^{i+1} - \tau_j^{i+1}}{\Delta t} = \frac{(v_{j+1}^i - v_j^i) \cdot \tau_{j+1}^{i+1}/\tau_j^{i+1} + \varepsilon}{w + v_{j+1}^i} \qquad (7)$$

Then we take the time derivative of $\tau_{j+1}^{i+1} - \tau_j^{i+1}$ by letting Δt approach zero to ensure that the formulation is physically well-defined (as in Laval and Leclercq (2008)). Since $\lim_{\Delta t \to 0}(v_{j+1}^i - v_j^i) = 0$ and $\lim_{\Delta t \to 0} \tau_{j+1}^{i+1}/\tau_j^{i+1} = 1$, the following ordinary differential equation (ODE) is obtained.

$$\frac{d}{dt} \tau^{i+1}(t) = \frac{\varepsilon}{w + v^i(t)} \qquad (8)$$

Assuming a constant acceleration rate $\beta > 0$ (thus, $v^i(t) = v^i(0) + \beta \cdot t$), a solution to the ODE with initial condition $r^i(0)$ gives

$$r^{i+1}(t) = \left(\frac{1}{r^{i+1}(0)} + \frac{\varepsilon}{\beta} \ln\left(1 + \frac{\beta \cdot t}{w + v^i(0)}\right) \right)^{-1} \qquad (9)$$

This equation is the dynamic formulation of the relaxation process following an LC maneuver. The solution presents the passing rate over time with parameters $r^i(0)$, $v^i(0)$, w, β and ε. As the model adopts macroscopic parameters to keep the model parsimonious, parameter estimations are done by obtaining average values across vehicles.

CALIBRATION OF THE RELAXATION PHENOMENON

This section describes our methodology to measure the relaxation dynamics based on the temporal evolution of passing rates. This methodology is employed to calibrate the LL model using vehicle trajectories.

Method to Calibrate the Relaxation Process

We now present our method to capture the relaxation dynamics and estimate the parameters. This method is based on passing rate measurements illustrated in figure 2. For illustration purposes, the method is described based on the relaxation of a lane-changer. The basic logic is that if an LC maneuver in queued traffic flow exhibits a relaxation process, then the passing rate would temporarily deviate from the equilibrium rate during relaxation. In view of this property, the method measures passing rates along a set of kinematic waves propagating at speed w, as illustrated in Figure 3. Note that the headway of the waves, h_w, is dictated by the time resolution of vehicle trajectories.
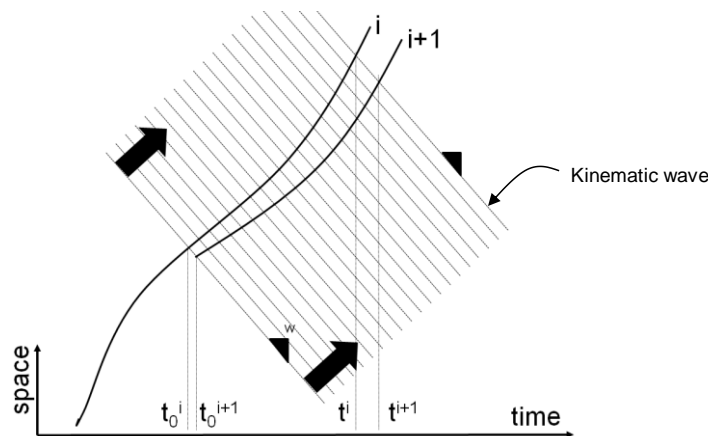

Figure 3 – The method to measure a relaxation process using the passing rate measurements along a set of kinematic waves

Let t_0^{i+1} denote the instant at which vehicle *i+1* maneuvers into the lane and responds to the behavior of the new leader (i.e. arrival of the first kinematic wave). The same wave crosses vehicle *i* earlier at t_0^i. Then, the passing rate along the first wave is $1/(t_0^{i+1} - t_0^i)$. Similarly, t^i denotes the latest time that the arrival of a wave is observable in the study section for vehicle *i*. Finally, t^{i+1} corresponds to the time at which the last wave propagates to vehicle *i+1*. The temporal evolution of the passing rate between vehicles *i* and *i+1* can be traced from t_0^{i+1} to t^{i+1} with an increment of h_w. Note that the study section needs to be long enough or an LC maneuver should occur near the upstream end of the section to capture complete relaxation processes.

Calibration Results

Trajectory data from two multi-lane freeway facilities are analyzed. The data from both freeways are available through NGSIM (2009). The schematics of the two freeway sites, Interstate 80 (I-80) and US 101, are shown in Figure 4(a) and 4(b), respectively. The details of data collection method and some preliminary analyses are provided in Hranac et al. (2004). In short, the trajectory data are available at the resolution of 1/10th of a second; the positions of each vehicle were recorded at 0.1 second intervals over 550 m (on I-80) and over 700 m (on US101). For each location, more than 5,000 vehicles were recorded during a 45-minute period. All general-purpose lanes are used in the analysis, excluding the high-occupancy-vehicle (HOV) lanes, since the HOV lanes typically exhibited different traffic states from the general-purpose lanes.
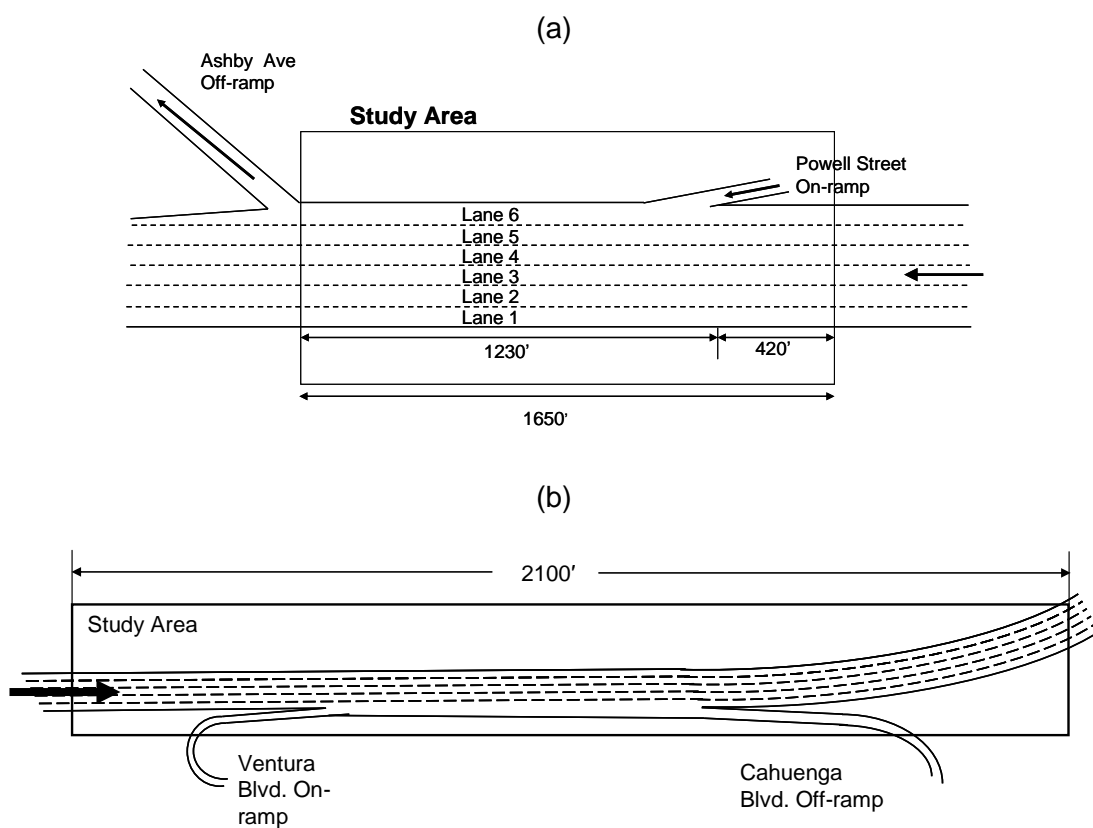
(a)

(b)

Figure 4 – Freeway sites where NGSIM vehicle trajectory data are obtained

(a) Eastbound Interstate 80 near San Francisco, CA

(b) Southbound U.S. 101 (Hollywood Freeway) in Los Angeles, CA

Results from the I-80 site

Of the vehicles in the dataset, we first identified pairs of lane changers and the lead vehicles in the target lanes (or pairs of lane changers and the immediate followers for analyzing the followers' relaxations). The lead vehicles and the followers must be non-lane-changers to

evade multiple relaxation processes. Only the vehicle pairs that initially exhibited deviation from equilibrium car-following behavior upon LC are included in our analysis. A lane changer (or the immediate follower) is assumed to have deviated from the equilibrium if the initial passing rate, $r(t_0^{i+1})$, exceeds 1 veh/s, since an average (equilibrium) passing rate without LC is observed to be about 0.7 veh/s (Chiabaut et al, 2009). The vehicle pairs are further filtered, so that the passing rate following an LC maneuver can be measured at least for 30 seconds. This criterion ensures that the method measures complete relaxation processes.

The proposed method to measure a passing rate requires w. Chiabaut et al. (2009) have already estimated w for individual lanes for the selected study sites; these values (≈ -5 m/s) are employed in this study. Moreover, $v_i(0)$ is taken as 5 m/s, which is the average speed of the leaders. A single value is used for all lanes as the average speeds were similar across lanes. Then, for each selected pair, the passing rate is measured every second. Figure 5 presents averages and the standard deviations of passing rates of all 197 selected pairs on I-80 during the relaxations of lane-changers as well as the immediate followers. The solid curve in the figure represents the best-fit curve based on equation (8). The figure reveals that the initial passing rate is around 1.6 veh/s, which is far larger than the equilibrium passing rate (≈ 0.7 veh/s). Then, the passing rate decreases at a decreasing rate and converges to the equilibrium after about 15 seconds. The observed relaxation duration of 15 seconds is consistent with previous findings (Leclercq et al., 2007; Ma and Ahn, 2008). The greater differences between the best-fit curve and observations toward the convergence are attributable to combining data for all lanes. This is remedied by separating lane 6 as will be explained shortly.
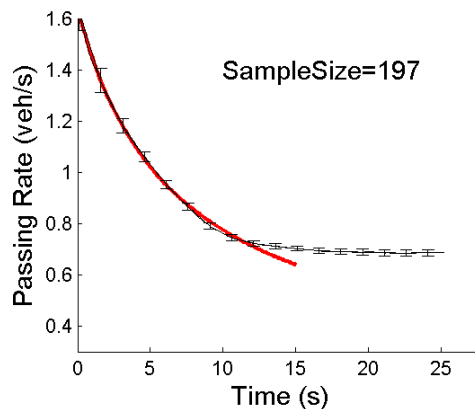

Figure 5 – Temporal evolution of (average and standard deviation) passing rates during relaxations for all regular-use lanes combined (lanes 2-6) for I-80

Next, we calibrate parameters β, ε and $r^i(0)$ in equation (8), which gives the best fit to the data (the solid curve in Figure 5). Table 1 shows the results of the calibration. The values in the parentheses represent lower and upper limits of the 95 percent confidence intervals. The estimated value of ε is around 1.32 m/s: a lane changer or the immediate follower is willing to accept the speed difference of 1.32 m/s during relaxation to resume a desirable (i.e., equilibrium) spacing. The estimated value of the initial passing rate, $r^i(0)$, is around 1.648 veh/s. The LL model is overall in good agreement with observation, as notable by relatively tight confidence bounds and a small root mean squared error (RMSE).

Table 1 **–** Calibration results of the LL relaxation model for all lanes (I-80)

	Lane-changers and immediate followers
ε (m/s)	1.32 (1.234[a], 1.396[b])
$r^j(0)$ (veh/s)	1.65 (1.627, 1.669)
β (m/s^2)	1.03 (0.778, 1.283)
RMSE	0.362
Relaxation Duration (sec)	15
Sample size	197

[a] the lower limit of 95 percent confidence bound
[b] the upper limit of 95 percent confidence bound

Leclercq et al. (2007) have observed a significant difference in the relaxation process between the shoulder lane (Lane 6) and the inner lanes (lanes 2 to 5) but no significant difference among the inner lanes. In view of this observation, the measured passing rates are combined only for lanes 2 to 5. Moreover, lane-changers and the followers are also separated to see if they exhibit similar relaxation processes. Figure 6(a) and 6(b) show the passing rates vs. time for the lane-changers and immediate followers, respectively, for lanes 2-5 and Figure 6(c) and 6(d) for lane 6. All four plots exhibit decreasing trends of passing rates which converge to the equilibrium passing rate of about 0.7 veh/s.
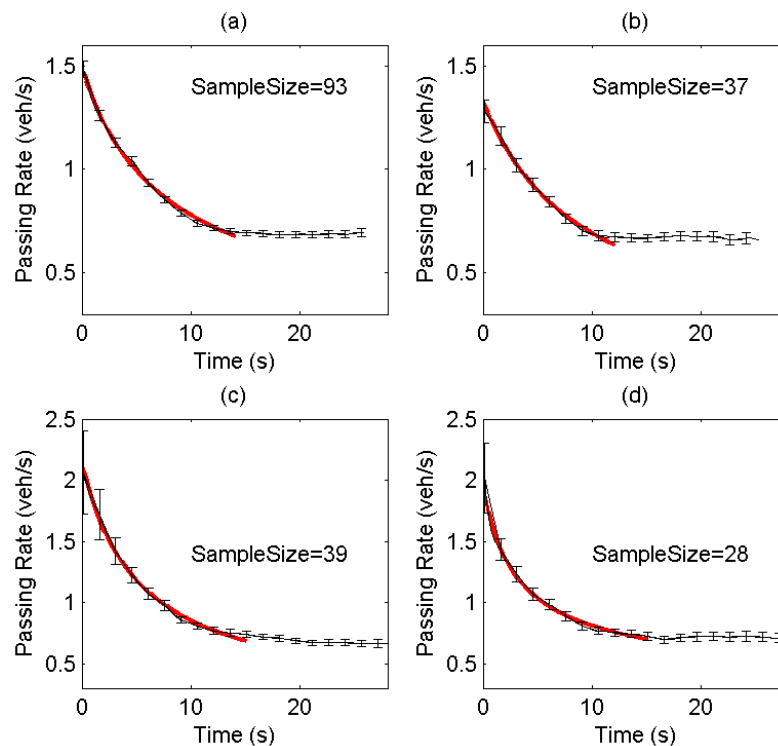

Figure 6 – Temporal evolution of (average and standard deviation) passing rates for I-80

(a) lane-changers in lanes 2-5; (b) immediate followers in lanes 2-5;

(c) lane-changers in lane 6; (d) immediate followers in lane 6

Table 2 presents the calibration results for different lane groups and relaxation types. The table shows that the parameters estimated for lanes 2 to 5 are indeed different from lane 6. The initial passing rate is notably higher on lane 6, indicating that lane changers accept very small spacing at the time of maneuvers in lane 6. This is attributable to mandatory LC maneuvers of merging vehicles from the nearby on-ramp. The relaxation parameter, ε, is also notably larger for lane 6: vehicles face very small spacing at the moment of maneuvers and accept much lower speed than their leaders presumably to resume their equilibrium spacings within a reasonable period. Not surprisingly, lane 6 exhibits a slightly longer relaxation duration than the inner lanes (15 seconds vs. 12-14 seconds). The estimated parameters for lane-changers and the immediate followers are also statistically different based on their confidence bounds: the relaxation behavior of a lane-changer is different from that of its follower. Finally, models for lanes 2-5 are in good agreement with observation based on small RMSE errors (less than 0.2) and tight confidence bounds. However, larger variations are observed for lane 6, particularly among lane-changers.

Table 2 – Calibration results of the LL relaxation model for lanes 2-5 and lane 6 (I-80)

	Lane-changers		Immediate followers	
	Lanes 2-5	Lane 6	Lanes 2-5	Lane 6
ε (m/s)	1.13 (1.067[a], 1.178[b])	1.22 (1.037, 1.352)	1.38 (1.240, 1.514)	1.93 (1.649, 2.220)
$r^i(0)$ (veh/s)	1.49 (1.473, 1.502)	2.13 (2.049, 2.219)	1.35 (1.328, 1.376)	1.94 (1.873, 2.009)
β (m/s^2)	0.72 (0.535, 0.9063)	0.50 (0.033, 1.24)	1.31 (0.8767, 1.75)	2.86 (1.85, 3.874)
RMSE	0.185	0.638	0.180	0.342
Relaxation Duration (sec)	14	15	12	15
Sample size	93	39	37	30

[a] the lower limit of 95 percent confidence bound
[b] the upper limit of 95 percent confidence bound

Results from the US101 site

The same calibration procedure was applied to the US 101 dataset, and the results are presented in Table 3. Of note, no observation was obtained from lane 6. This is not surprising since there are many weaving activities due to the proximity of the on- and off-ramps, which might have limited observation of relaxation processes over time without interruptions from other LC maneuver. The estimated parameters for lanes 2-5 on US 101 are slightly different from the counterparts on I-80. This is rather expected since the parameters likely depend on roadway geometry, rules and other factors. Moreover, unlike the results from the I-80 site, the parameter values are statistically indifferent between lane-changers and the immediate followers. Nevertheless, US101 site exhibited similar durations of relaxation ($\approx$ 15 seconds) based on the convergence of passing rates. Finally, the

calibrated models are in good agreement with observation (RMSE < 0.25) despite the small sample sizes.

Table 3 – Calibration results of the LL relaxation model (US 101)

	Lane-changers	Immediate followers
	Lanes 2 to 5	Lanes 2 to 5
ε (m/s)	1.05 (0.935, 1.173)	0.99 (0.839, 1.157)
$r^j(0)$ (veh/s)	1.44 (1.415, 1.471)	1.47 (1.423, 1.516)
β (m/s^2)	0.75 (0.352, 1.152)	0.64 (0.372, 0.897)
RMSE	0.177	0.222
Relaxation Duration (sec)	16	15
Sample size	22	11

POST-RELAXATION IMPACTS OF LANE-CHANGING

The method presented in Section 4 measures the dynamic process of a vehicle's relaxation based on the temporal evolution of passing rates. The results indicate that lane-changers and their immediate followers in the target lanes eventually converge back to their equilibrium car-following behavior. This implies that a post-relaxation impact of a vehicle insertion is nothing more than an added vehicle to the traffic stream. However, the method does not capture the cumulative effect of multiple maneuvers, e.g., the cumulative effect of an insertion (exit) maneuver followed by another insertion (exit). This section presents a method to assess the impact of multiple LC maneuvers using passing rate measurements, after the relaxation processes are (nearly) complete. Notably, the cumulative impact of multiple maneuvers are quantified within a platoon of 10 or more vehicles by measuring variations in passing rates along kinematic waves before and after LC maneuvers and relaxations.

Method to Measure Lane-changing Impacts

Figure 7 illustrates the method to measure the impacts of (multiple) LC maneuvers. Figure 7(a) shows a platoon of N vehicles behind vehicle 0 and propagation of a kinematic wave through the platoon. Then, the maximum passing rate, r, of the kinematic wave is the harmonic mean of individual passing rate, r_i. Note that measuring the harmonic mean is straightforward since,

$$r = \left(\frac{1}{N} \sum_{i=1}^{N} \frac{1}{r_i} \right)^{-1} = \left(\frac{1}{N} \sum_{i=1}^{N} \tau_i \right)^{-1} = \frac{N}{(t_N - t_0)} \qquad (10)$$

where N is the platoon length (in vehicles), t_0 and t_N are the times at which the wave intersects the reference and the Nth vehicles, respectively.

A platoon is selected in such a way that both a reference vehicle and its *Nth* follower do not change their lanes on the study section. Then, the passing rates are measured along two parallel kinematic waves with speed *w* as shown in Figure 7(b): the first wave, W_1, in the beginning of the study section and the second wave, W_2, at the end of the section. W_1 intersects with vehicles *0* and *N* at points (t_1,x_1) and (t_2,x_2), respectively. Thus, the maximum passing rate along this wave is estimated by: $r_1=N/(t_2-t_1)$. Similarly, W_2 crosses vehicles *0* and *N* at (t_3,x_3) and (t_4,x_4), respectively, and the corresponding passing rate is estimated by: $r_2=(N+N_{net})/(t_4-t_3)$, where N_{net} is the net number of insertion(s) between vehicles *0* and *N* in the region bounded by W_1 and W_2. The r_1 and r_2 are measured in the absence of relaxations by ensuring that no LC occurs in "buffer" regions **A** and **C** (shaded areas in Figure 7(b)). The horizontal distances of these regions correspond to $T_{relax}*(1+v/w)$, where T_{relax} is the relaxation duration and *v* is the average speed of vehicles in regions **A** or **C**. Thus, any difference between r_1 and r_2 indicates an overall impact of LC maneuvers after relaxations. Note that the method requires a single parameter, *w.*

Figure 7(c) shows an example with real trajectories from I-80 on lane 2 (lane next to the HOV lane). This platoon has one net insertion; two insertions and one exit as marked by ○ and +, respectively.
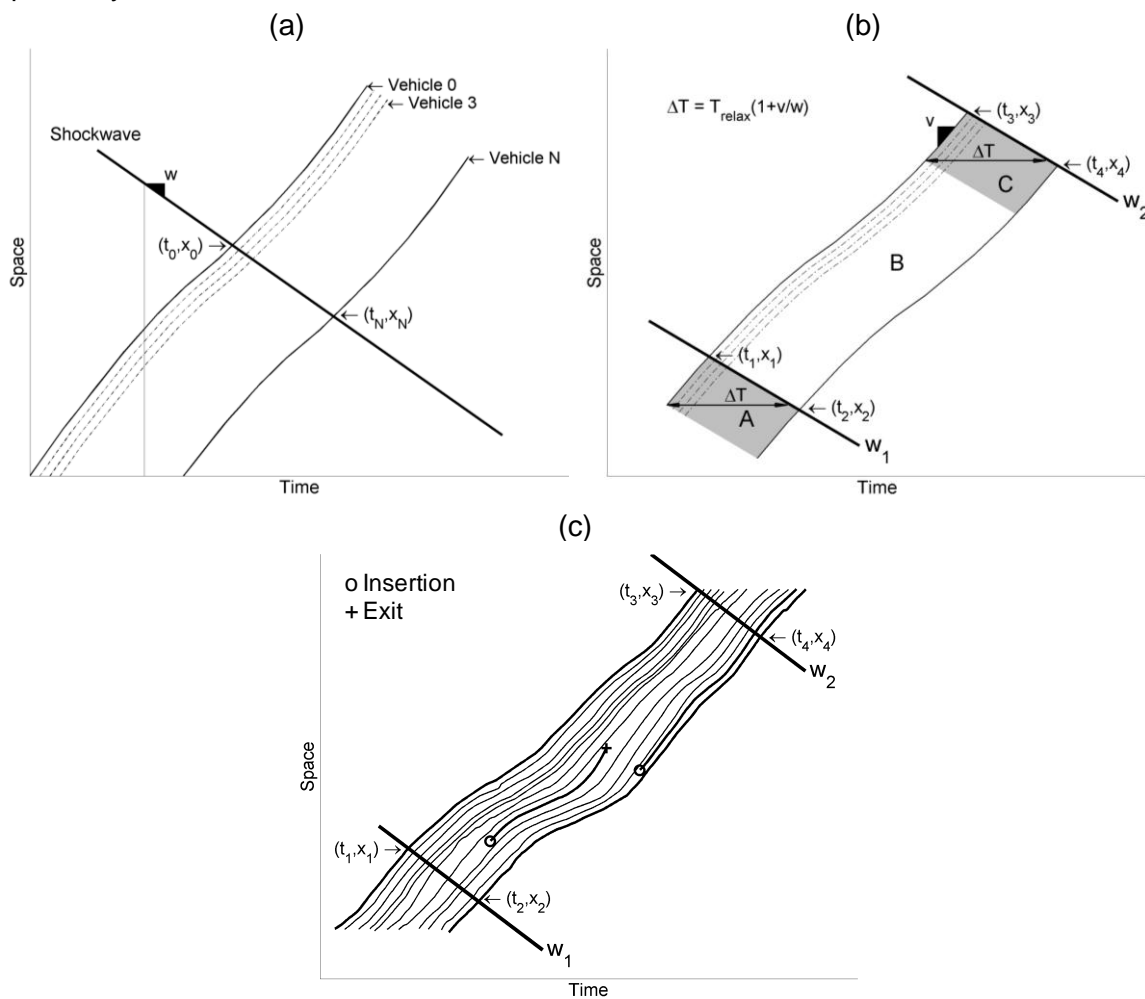
(a)

(b)

(c)

Figure 7 – (a) Illustration of the method to measure the passing rate over a platoon
(b) Methodology to measure the cumulative impact of lane-changing within a platoon of *N* vehicles

Chiabaut et al. (2009) note that the harmonic mean of individual w_i's converges to w with 10 vehicles. Thus, N is set to be 10 for platoons with positive N_{net} while $N+N_{net}$ is set to be 10 for platoons with negative N_{net} to guarantee the level of confidence.

The passing rate would remain constant in absence of LC (i.e., $r_1 = r_2$) since passing rates of individual vehicles are independent of their speed (Chiabaut et al., 2009). Also note that $r_1 = r_2$ if the post-relaxation effect of LC maneuvers is simply adding or subtracting vehicles without additional impact (e.g., change in driving behavior).

Empirical Findings

The overall impact of LC maneuvers has been analyzed for I-80 and US101 combined since both freeway locations exhibited similar equilibrium passing rates of about 0.7 veh/s (0.68 veh/s for I-80 and 0.73 veh/s for US101). No platoons were identified from the shoulder lane (lane 6) due to frequent LC maneuvers from the nearby ramps. Of note, the horizontal distances of regions **A** and **C** (see Figure 7(b)) should be 30 seconds since the relaxation duration is found to be around 15 seconds, and w and v are respectively -5 m/s and 5 m/s. However, this buffer duration was too large to observe multiple LC maneuvers in region **B** (see again Figure 7(b)). We selected 15 seconds instead as the buffer duration (i.e., 7.5 seconds for relaxation buffer) to obtain sufficient samples. This is large enough to measure r_1 and r_2 nearly free of LC relaxations. Specifically, Figure 6 indicates that the passing rate decreases from 1.648 to about 0.85 within 7.5 seconds into the relaxations. Figure 8 elaborates the percent completion of a relaxation over time based on the estimated parameters in Table 1 and an equilibrium passing rate of 0.7. It is clear that convergence to the equilibrium passing rate occurs quite quickly in the beginning and that more than 80 percent of the relaxation is complete after 7.5 seconds.
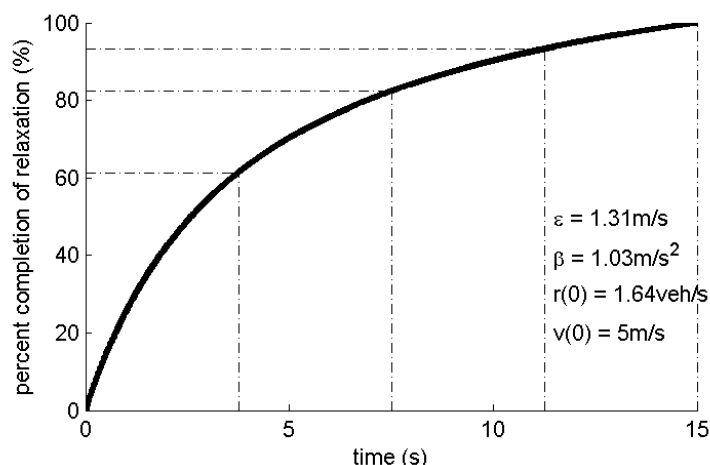

Figure 8 – Percent completion of relaxation processes over time for all regular-use lanes on I-80

The selected platoons are divided into two groups: one with no exit maneuvers and 0, 1 or 2 insertion maneuvers within the platoons, and one with no insertion maneuvers and 0, 1 or 2

exit maneuvers. Thus, in the first (second) group, one can observe the effects of multiple insertions (exits) by comparing r_1 and r_2. Figure 9 shows the averages and the 95 percent confidence bounds for group 1 with 0, 1 and 2 insertions. The results show that the average values of r_1 and r_2 are close to 0.7 veh/s and that for all the cases treated here, the differences between r_1 and r_2 are not significant at the 95 percent confidence level. This indicates that lane-changers or the immediate followers in the target lanes resume "normal" spacings after relaxations. Moreover, the results for group 2, shown in Figure 10, are similar to those for group 1. No statistically significant differences are observed between r_1 and r_2, indicating that vehicles following the lane changers in the initial lanes accelerate and fill the voids created by the maneuvers. The results from both groups indicate that lane-change maneuvers do not have long-term effects in congested traffic streams once relaxations or acceleration processes to fill voids are complete.
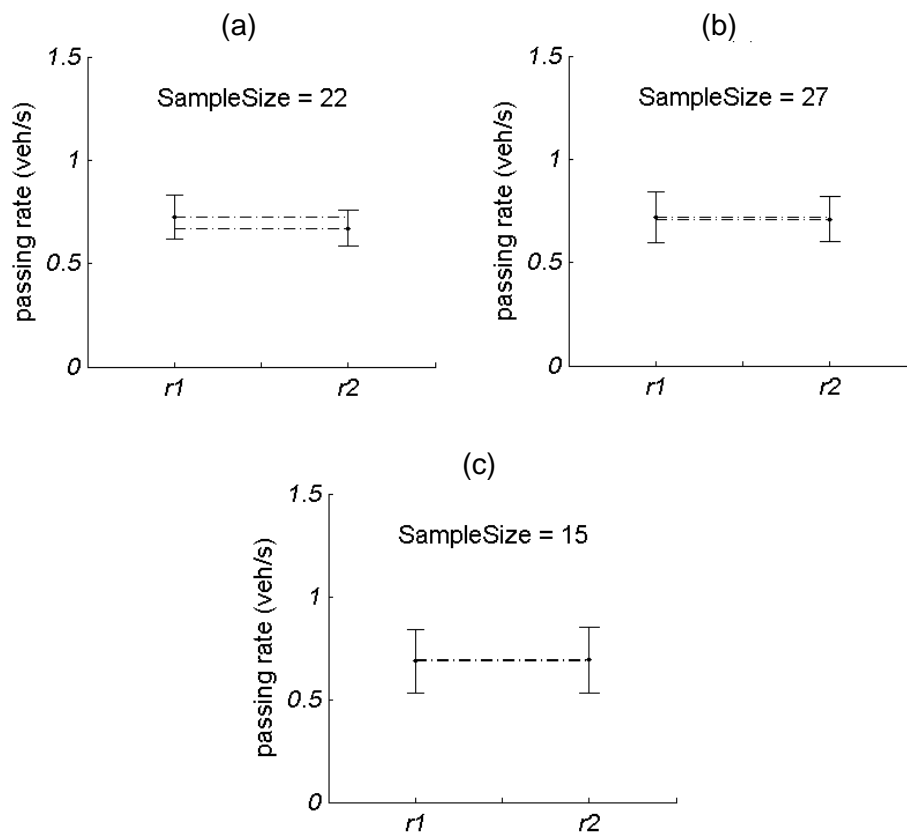

Figure 9 – 95 percent confidence bound for r_1 and r_2 with zero exit maneuvers

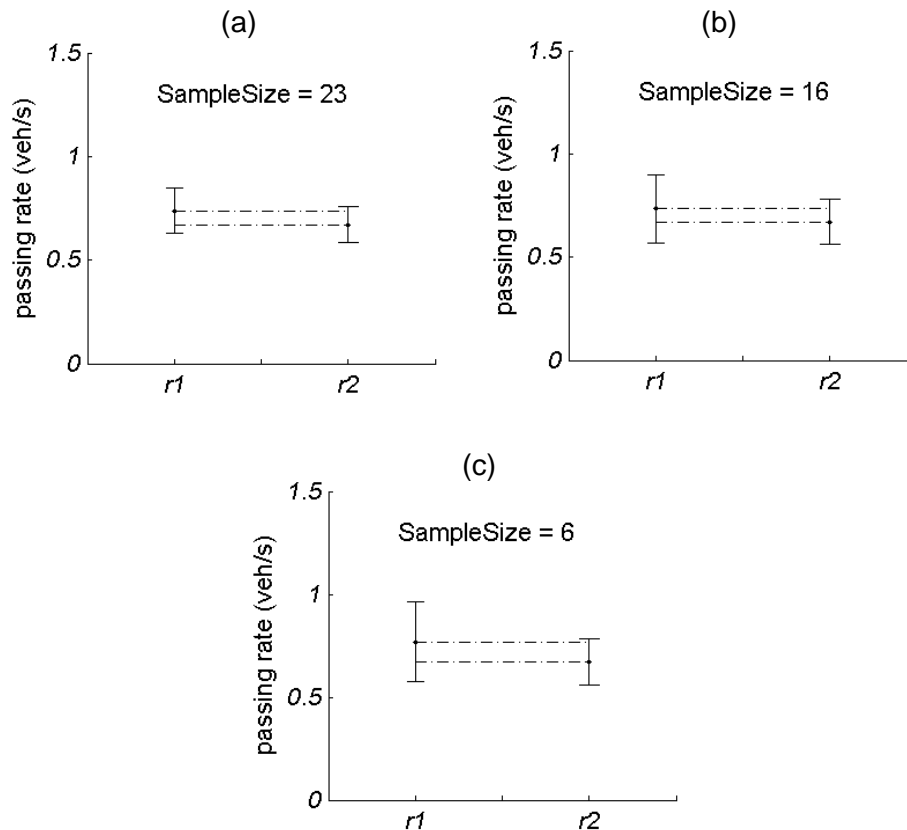(a) zero insertions; (b) one insertion; (c) two insertions

Figure 10 – 95 percent confidence bound for r_1 and r_2 with zero insertions

(a) zero exit maneuvers; (b) one exit maneuvers; (c) two exit maneuvers

CONCLUSIONS

In this paper, passing rate measurements with backward moving kinematic waves as moving observers are employed to measure traffic features around lane-changing maneuvers. The basic principle is such that a perturbation in traffic state due to lane-changing maneuvers is reflected in the passing rate measurements.

We first examined the relaxation processes of lane-changers and the immediate followers by observing the temporal evolution of their passing rates. The analysis of the NGSIM vehicle trajectories show that the passing rate jumps to a large value upon a vehicle insertion and then decreases at a decreasing rate prior to reaching an equilibrium ($\approx$ 0.7 veh/s). This relaxation took about 15 seconds, which is consistent with earlier findings. The passing rate measurements were also used to calibrate and verify the modified formulation of Laval and Leclercq's simple relaxation model. The results showed that the simple relaxation model match the real observations well. However, the results also show that the model performance is inferior and the estimated parameters are different for the shoulder lane. The study site includes a busy merge, where many mandatory merging maneuvers occur onto the shoulder lane, which may induce more variable traffic dynamics. A further study is deemed necessary

to better understand the mandatory lane-changing behavior in the shoulder lane. Moreover, due to the insufficient amount of trajectory data, a validation of the revised model has not been conducted in this study. Thus, future validation efforts are necessary to confirm our findings although our calibration method is rigorous, and the results are convincing.

The passing rate measurements were also employed to quantify the post-relaxation impact of multiple lane changing maneuvers within a platoon of 10 or more vehicles in congested traffic stream. The analysis of the same vehicle trajectories show that the variations in the passing rates before and after lane-changing maneuvers were close to zero (once the relaxation processes are complete), indicating that lane-changing maneuvers do not induce a long-term change in traffic streams.

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