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Spatio-Temporal Analysis of Impacts of Lane Changing Consistent with Wave Propagation

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ABSTRACT

This paper is concerned with the impacts of lane-changing maneuvers in traffic streams. A new methodology is developed based on the simplified kinematic-wave theory and only requires one assumption: a constant speed of the backward-moving characteristic along a large platoon of vehicles. This method consists in quantifying the net impact of entering and exiting-lane changing maneuvers among a platoon of fifteen vehicles. It has been applied to two highway trajectory datasets from the NGSIM program. Findings from this study show that the impact of lane-changing depends on the net number of entering vehicles to a lane, and insertions have greater impacts in traffic stream than exits.

1. INTRODUCTION

Traffic congestion is a serious externality of modern society and has negative societal and environmental impacts. Notable features of congestion are capacity reductions of freeway bottlenecks and oscillations (i.e. stop-and-go traffic), which are directly related to the amount of delay, engine emission and fuel consumption. Thus, control strategies that address the causal factor(s) of these phenomena are critical in alleviating congestion-related problems. In recent studies, lane-changing (LC) has been identified as a primary causal factor for these traffic instabilities (1-3). However, existing literature does not provide a comprehensive understanding of LC related processes, particularly in regard to its impact on traffic streams (e.g. flow, density, etc.).

In response to the evident need for empirical research on LC, the present study deals with quantifying the effect of LC in traffic streams. Notably, the impacts of both entering and exiting maneuvers are quantified and evaluated for their net effect on the traffic upstream. Our method to quantify the LC effect exploits the principle of Newell's car-following model (4) that predicts the positions of each vehicle over time (in the absence of LC maneuvers) with few parameters directly observable in the field. The impacts of LC maneuvers are then measured as discrepancies between actual observations and Newell's predictions. The results show that the net number of insertions is the most significant factor; i.e., the impact increases with respect to increases in net number of insertions. The results also show that insertions have more significant impact than exiting maneuvers.

The remainder of the manuscript is organized as follows. Section 2 summarizes existing literature related to LC models and efforts to evaluate the effects of LC. In section 3, the study sites and their trajectory data are described. Section 4 describes the methodology developed in this study to properly measure the impact of LC maneuvers. Empirical findings based on the new methodology are presented in section 5, and some concluding remarks are provided in the last section.

2. BACKGROUND

Recent experimental studies have shown that LC is a causal factor for several important traffic phenomena. Cassidy and Rudjanakanoknad (1) conducted an empirical study to observe the causes of a reduction in discharge rate when a recurrent merge bottleneck activates on a freeway. They observed that when the inflow from an on-ramp was sufficiently large, the accumulation in the freeway shoulder (right-most) lane immediately upstream of the merge increased. When the accumulation reached a "critical" level, vehicles in the shoulder lane maneuvered toward faster, left lanes in attempts to increase their travel speeds, causing traffic breakdown in left lanes and decreasing the overall discharge rate through the bottleneck. The capacity drop was observed to be around 10 percent, which is consistent with findings from other bottleneck studies (1, 5-8).

In Ahn and Cassidy (3), it was shown that LC maneuvers are a primary cause for freeway oscillations (e.g. stop-and-go traffic). They systematically detected about twenty instances of oscillations' formations and growths using trip times of individual vehicles. Vehicle trajectories around those detected instances revealed that LC maneuvers were directly linked to the instances of formations and growths.

These studies, however, illustrate the causal relationship in a qualitative manner (3) or at a macroscopic scale by correlating LC rates to the occurrence of capacity drop (1). Thus, the impacts of LC maneuvers are not quantified at a microscopic level in these studies.

Modeling LC processes and predicting their roles in traffic dynamics involve three primary elements: LC decision, relaxation upon LC and impacts in traffic streams. The decision process, whether to change lanes, is realized as the rates of LC given traffic conditions. The LC relaxation occurs when a lane-changer and/or its immediate follower accept spacings that are out of the equilibrium car-following behavior and then resume equilibrium spacings gradually. Finally, this relaxation process, along with the behavior of the followers in the initial and target lanes, governs the evolution of traffic upstream.

Current literature provides a wealth of research on the decision process, especially in the framework of microscopic simulations. Gipps (9) provided a framework to model the decision process of LC, which consisted of three primary steps to assess necessity, desirability and feasibility of an individual LC maneuver. Many LC models emerged based on this framework, especially to model the motivation for LC (i.e. desirability). Examples include models based on discrete choice theory (e.g. 10-12) and models based on Fuzzy Logic (e.g. 13). However, 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 consequently, the results obtained from the models may be less meaningful. The same concern prevails in various gap acceptance models to describe feasibility of LC executions as these models also include behavioral parameters such as “critical time gap”, a minimum time gap necessary to safely execute an LC maneuver. Finally, these studies focused more on the decision process of LC rather than its impacts in traffic streams.

Laval and Daganzo (14) developed a parsimonious model in the framework of the kinematic wave (KW) model of Lighthill and Whitham (15) and Richards (16) (LWR). Unlike the earlier extensions of the LWR model (e.g. 17-20) which treat LC maneuvers as fluid with instantaneous acceleration, this model treats LC maneuvers as particles with realistic properties such as bounded acceleration. Furthermore, the model treats each lane as a separate KW stream with a lane-changer as a moving bottleneck that blocks the entire lane. LC rates (i.e. LC decision) are determined based on speed difference in neighboring lanes. The model involves four parameters that are physically meaningful and are easily measured from data. The model is able to reproduce the reduction in bottleneck discharge rate and the capacity of a moving bottleneck in relation to its speed. The mechanism of capacity reduction was such that LC maneuvers near an active bottleneck create voids in traffic streams and thus reduce discharge rate. It was verified empirically that the model reproduces various features, such as lane-changing rates and amount of capacity reduction, around a merge bottleneck (21).

Laval and Leclercq (22) later introduced an application of this model in a microscopic framework by incorporating car-following rule (4, 23) and treating individual LC maneuvers as moving bottlenecks. Moreover, the model incorporates LC relaxation phenomenon which has been observed in earlier studies (e.g. 24) and was later validated and calibrated (25, 26). Although these models are successful in reproducing important macroscopic traffic features, such as capacity reduction, the impacts of individual LC maneuvers were not explored explicitly at a microscopic level.

It was Coifman et al. (27) who first explicitly studied the impact of LC at a microscopic level. Notably, they attempted to measure the delay due to LC maneuvers in relation to the number of entering and exiting vehicles. Delay was taken as the difference between a vehicle’s actual travel time and its estimated travel time if the vehicle were not influenced by any LC maneuvers occurred downstream. The latter travel time was estimated by the algorithm developed by Coifman (28). The algorithm assumes a constant, definite speed of characteristics (i.e. kinematic waves) independent of traffic conditions as well as drivers. Then, the speeds observed at a particular location reflect traffic states propagating from

downstream at the definite speed of wave known a priori. Based on these assumptions, the trajectory of each vehicle is estimated based on observations taken at the upstream end of a study section (near a merge on Interstate 405 in Los Angeles). The results from regression analysis show findings consistent with expectations, such that entering vehicles result in delay while exiting vehicles result in savings in delay. Moreover, based on the estimated parameter values from a linear regression, delay caused by entering vehicles was found to be larger than savings in delay by exiting vehicles.

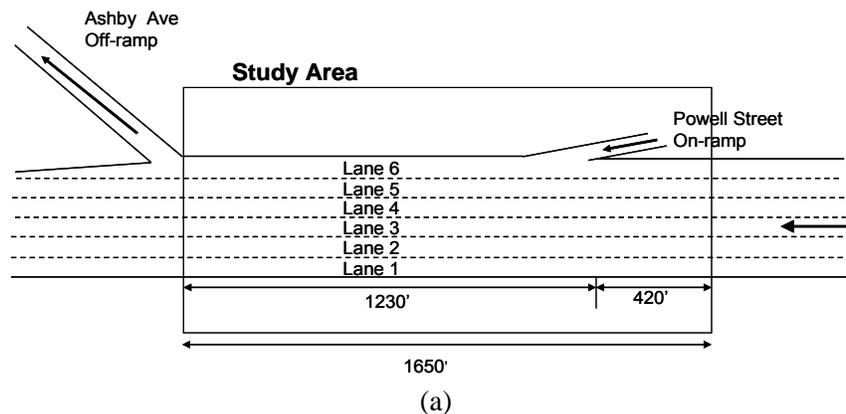
The study by Coifman et al. (27) provides great insight on the impacts of LC maneuvers. However, as noted in their paper, the study bears some shortcomings, and a further investigation is necessary to provide a better understanding of LC impacts. Namely, the relaxation process of LC maneuvers was not taken into consideration. Thus, it is suspected that the study by Coifman et al. does not entirely exclude the impact of LC maneuvers executed outside the delay measurement areas and equally importantly, does not entirely measure the full impact of LC maneuvers in the measurement areas.

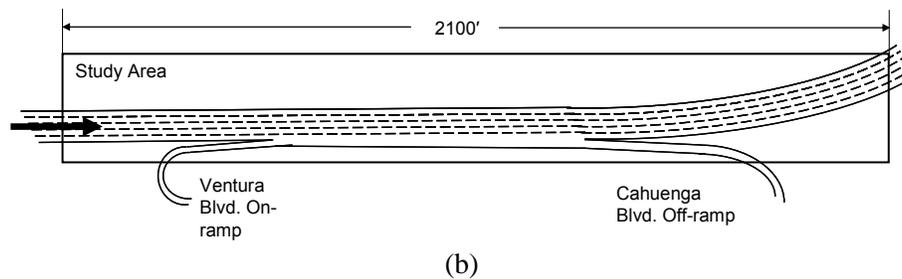
To this end, a new method is developed to measure the LC impacts including its relaxation processes. The method in this study is developed in the spirit of the simplified KW model of Newell (29) in light of previous findings that certain extensions of such continuum model (e.g. 14) are able to reproduce important traffic phenomena such as capacity drop. Thus, Newell's car-following model (4, 23), a microscopic model consistent with the macroscopic model of Newell (29), is used to study the LC impacts at a microscopic level. In particular, Newell's car-following model is used to predict trajectories of vehicles assuming no LC effect and to compare them with actual ones to quantify the discrepancies.

3. SITES AND DATA

Trajectory data from two multi-lane freeway facilities are analyzed. The data from both freeway locations are made available by the FHWA's Next Generation Simulation (NGSIM, URL: <http://ngsim.fhwa.gov/>) program. The schematics of the two freeway sites, Interstate 80 and US 101, are shown in Figures 1(a) and 1(b). The details of data collection method and some preliminary analyses are provided in Hranac et al (30). In short, the trajectory data are available at the resolution of 1/10th of a second; i.e., the positions of each vehicle were recorded at 0.1 second intervals over 550 m (in I-80) and over 700 m (in US101). For each location, over 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 they typically exhibited different traffic states from the general-purpose lanes. The right-most lane (Lane 6) was also excluded in the analysis due to excessively frequent lane-changing. As explained later in the manuscript, our method requires every several vehicles to traverse the entire study section without lane-changing. However, the data from the right-most lane did not include enough number of non-lane-changers to perform such analysis.





(b)

FIGURE 1 Freeway Sites
 (a) Interstate 80 Eastbound
 (b) U.S. 101 (Hollywood Freeway) Southbound

4. METHOD TO MEASURE LANE-CHANGING IMPACTS

The overall logic of our method to measure LC impacts is as follows. It is assumed that the car-following behavior in the absence of LC is described by Newell (4) as supported by recent empirical studies (31-34), and Duret et al. (33) and Chiabaut et al. (34) verified this using the same NGSIM dataset. Thus, the trajectory of each vehicle is estimated according to Newell's theory given a reference leader, representing the trajectory if there were no LC maneuvers between the vehicle and the reference leader. The impact of LC maneuvers is then measured along characteristics (i.e. kinematic waves) as a displacement in time and location of the actual trajectory from the estimated one. The details of the method to measure the impacts of LC are described below including a short description of Newell's car-following theory.

The car-following model proposed by Newell involves few parameters and uses logic that is different from conventional car-following models such as stimulus-response based models. In this theory, a driver selects his spacing for a given speed in such a way that under congestion regime his trajectory replicates his leader's only with a displacement in time and space. In Figure 2(a), τ_j and d_j correspond to the displacement in time and space for vehicle j in response to the leader's speed change from v to v' . Thus, the disturbance propagates from vehicles $j-1$ to j at the speed of d_j / τ_j . The model assumes constant values of τ_j and d_j for each individual vehicle independent of their speeds. This implies that the relationship between spacing and speed for a vehicle is linear (since spacing of vehicle j , $s_j = d_j + \tau_j v$) as illustrated in Figure 2(b), and that the propagation speeds of disturbances are constant independent of vehicle j 's speed. Finally, τ_j and d_j are assumed to come from a joint distribution such that a disturbance propagates from one vehicle to another as a random walk. The mean speed of disturbance is d / τ , where d and τ are the mean values of spatial and temporal translation. At the macroscopic level, this simple car-following model corresponds to triangular flow-density relations as shown in Figure 2(c).

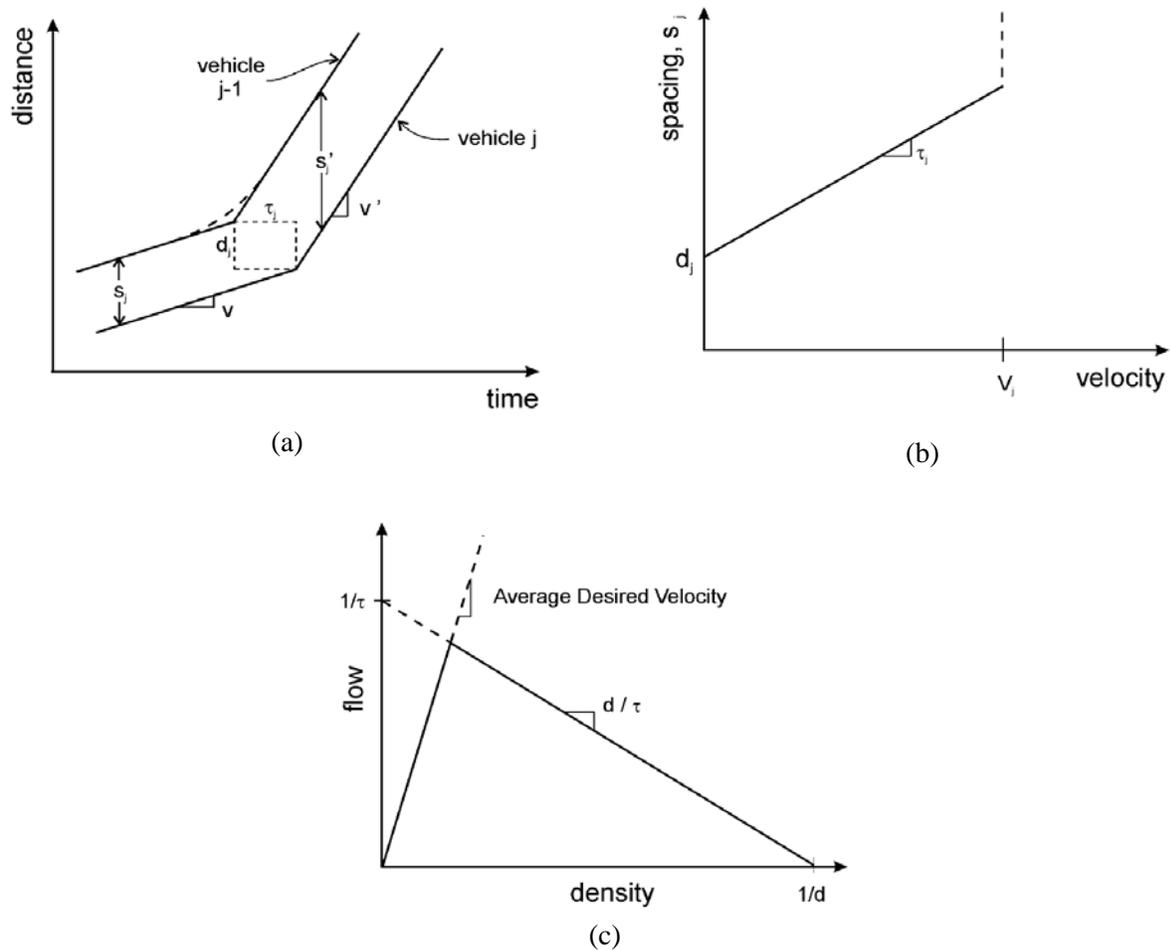


FIGURE 2 Illustration of Newell's Car-Following Theory
 (a) Vehicle Trajectories (adopted from Newell (2002))
 (b) Speed-Spacing Relationship for Vehicle j (adopted from Newell (2002))
 (c) Flow-Density Relationship (adopted from Ahn and Cassidy (2004))

In this study, it is assumed that a disturbance propagates as a random walk as per Newell's theory and that the speed of the kinematic wave (measured with respect to the reference vehicle) converges to the average value, d / τ , when it reaches the n th vehicle. As noted in (35), as n increases, the wave speed will converge to its mean, and the confidence interval of the mean will decrease. The n was set to 15 in light of the finding in (35) that the convergence to the average beyond 15 vehicles was ensured within 2% error. Then, the effect of LC maneuvers is quantified for the 15th vehicle upstream. This approach was adopted to account for the differences in wave speeds due to driver differences and work with the average wave speed which was rather straightforward to measure from available data.

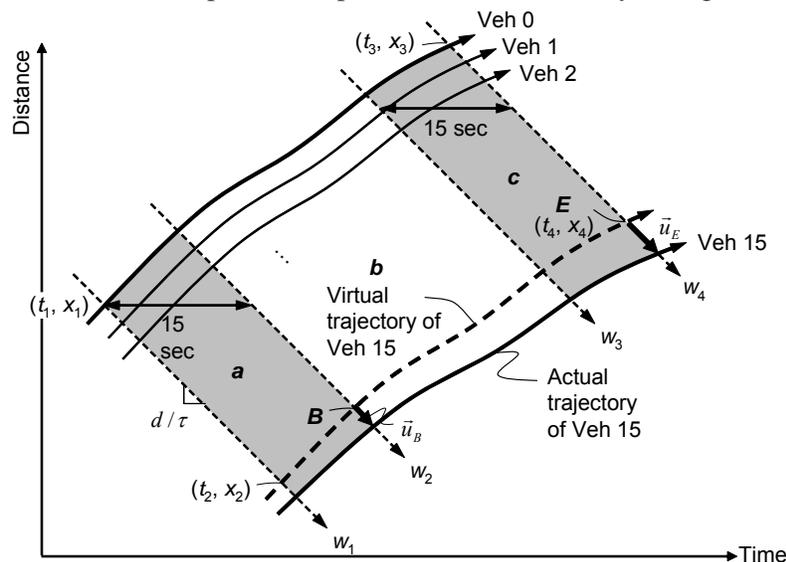
Figure 3 illustrates in detail the way in which LC impact was measured. The analysis begins by simulating the trajectory of vehicle 15 (a bold dashed trajectory in the figure) with respect to the reference vehicle (vehicle 0 in the figure) according to Newell's car-following model. Thus, $t_2 - t_1$ (and $t_3 - t_4$) is the sum of τ_j 's for vehicles 1 through 15, which is estimated as $15 * \tau$, while $x_1 - x_2$ (and $x_4 - x_3$) corresponds to $15 * d$. (It should be clear that the sum of the τ_j 's simulated for vehicles 1 - 15 converges to $15 * \tau$ as per (35).) The speed of four kinematic waves, $w_1 - w_4$, in Figure 3(a) is then d / τ . Chiabaut et al. (34) have previously determined all parameters associated with Newell's model (i.e. the parameters for the joint

distribution of τ_j and d_j) for the same dataset, and thus, the same parameter values of τ and d are used for simulating trajectories. Note that point (t_1, x_1) is selected to ensure that w_1 propagates through 15 vehicles upstream before reaching the upstream end of the study section, and (t_3, x_3) is selected at the downstream end.

Next, the relaxation processes of LC maneuvers of interest are accommodated. For this, it is made certain that there is no LC maneuver in region **a** (a lower-left shaded area in Figure 3(a)), whose horizontal distance corresponds to a maximum relaxation time. In light of the findings from previous studies (24-26), 15 seconds was used as the threshold. Thus, it is assumed that the relaxation of any LC occurrence below w_1 is completed in or before region **a**. Similarly, it is also made certain that region **c** (the upper-right shaded area in Figure 3(a)) is free of LC since the relaxation of a maneuver in this region would likely be completed above w_4 . Then, the impact of all lane-change maneuvers in region **b** is measured along the trajectory of vehicle 15 between points **B** and **E**.

The impact of LC maneuver(s) is measured by comparing the virtual and actual trajectories of vehicle 15. In Figure 3(a), the \vec{u}_B represents the displacement of the actual trajectory by the random error in estimating the trajectory if there were no LC maneuvers. The \vec{u}_E represents the displacement by the estimation error and also by LC maneuver(s). Thus, $\vec{u}_E - \vec{u}_B$ is the impact of LC, and its magnitude, $\|\vec{u}_E - \vec{u}_B\|$, captures the displacement in time (i.e. delay) and in position due to LC maneuvers. Notice that, as shown in Figure 3(b), this is equivalent to measuring the length of the difference in vectors, $\|\vec{u}_E' - \vec{u}_B'\|$, which are measured with respect to the reference vehicle along the characteristics. For computational efficiency, the latter measurement illustrated in Figure 3(b) is used. The latter method requires only one parameter of the average speed of wave, rather than separate observations of τ and d as in the first method. The average wave speed is easily measured from trajectory or loop detector data. Finally, note that the impact we measure is the cumulative effect of all entering and exiting LC maneuvers rather than a single maneuver.

An example with real trajectories is shown in Figure 3(c). The figure illustrates a case with two insertions and two exits as marked by circles. The bold dashed trajectory represents a simulated trajectory of vehicle 15, corresponding to a simple shift of the leader of the platoon in the absence of lane changes. At the downstream end of vehicle 15, the simulated trajectory lies left to the actual one, indicating that the two insertions and two exits resulted in positive impact (i.e. additional delay) along the characteristic.



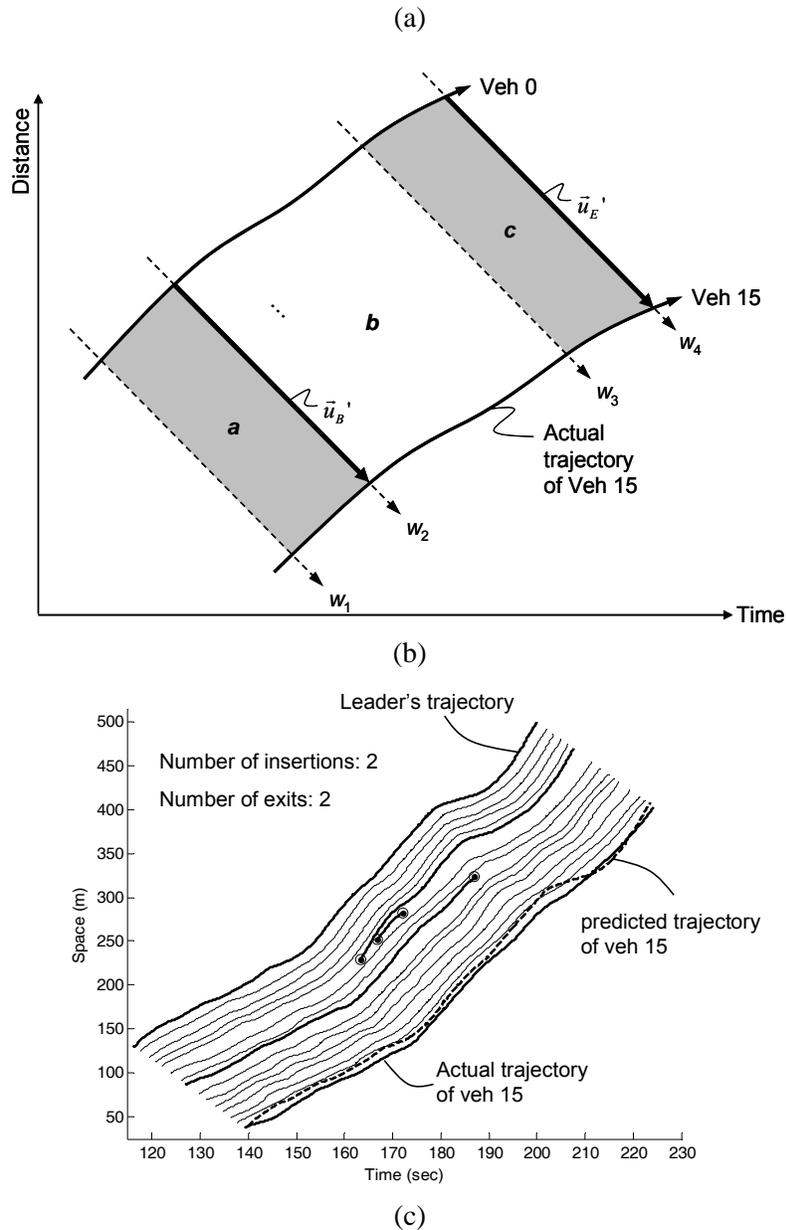


FIGURE 3
 (a) Illustration of Method to Measure LC Impact
 (b) Simplified Method
 (c) Example Trajectories with Two Insertions and Two Exits

5. EMPIRICAL RESULTS

Based on the method described in the previous section, a total of 48 (61) independent samples were obtained from I-80 (US 101). Table 1 presents the sample size for each composition of the numbers of insertions and exits. Most of these samples came from the left two lanes as there were few instances where both vehicles 0 and 15 traversed the entire study section without changing their lane.

As shown in Table 1, there were two observations of no LCs, (0 insertions, 0 exits) for I-80 (but no observation on US101). The impacts for these cases should be close to zero if Newell's theory holds. The

measured impacts are -1.54 and 3.02, which correspond to -1.5% and +2.8% error in position along the characteristics since $\|\bar{u}_B\|=107$ ($d=7\text{m}$ and $\tau=1.4\text{sec}$). Note that this error term precludes the calibration error, \bar{u}_B in Figure 3(a), due to the randomness of individual drivers and represents the error of assuming Newell's model. Although a rigorous statistical testing could not be done due to the small sample size, the result supports the validity of Newell's car-following theory and thus our method to measure the impact of LC.

TABLE 1 Sample Size of Each Composition of Numbers of Entries and Exits

		No. of Exits													
		I 80							US 101						
		0	1	2	3	4	5	6	0	1	2	3	4	5	6
No. of Entries	0	2	8	1	0	0	0	0	0	0	0	0	0	0	0
	1	3	5	1	0	1	0	0	0	5	1	1	1	1	0
	2	3	1	4	3	2	0	0	0	4	3	2	2	2	0
	3	1	0	0	1	3	1	0	0	2	2	3	0	0	0
	4	0	0	1	1	2	0	0	0	2	2	3	3	1	0
	5	0	0	1	1	0	0	0	0	2	2	2	3	1	3
	6	0	0	0	1	1	0	0	0	1	0	0	3	2	2

Figures 4(a)-(c) show the relationships between the measured impact and number of insertions, number of exits and net number of entries for the I-80 site, respectively. They show that the effect of LC vs. the number of insertions (Figure 4(a)) or exits (Figure 4(b)) does not display clear patterns. This is not surprising as the magnitude of LC impact is likely to depend on both factors combined. As shown in Figure 4(c), the measured LC impact increases with respect to the increases in number of net insertions (number of insertions – number of exits), which is consistent with the findings from Coifman et al. (27). Also, the scatter reveals a relation that is approximately linear, which is more pronounced with the average impacts by the net number (circles in the figure). A linear trend line is shown in Figure 4(c) as well as the corresponding linear model and R^2 . These were obtained via the weighted least squares method using the averages by the net number. The weight corresponds to the number of observations for each net number of insertions. The model parameters are statistically significant (based on a regression analysis). The intercept term (4.06SI) is positive, implying that if the same number of insertions and exits occur, we expect to observe a larger impact by insertions and thus, a positive displacement in trajectory along characteristics. (The unit of an LC impact is $(\text{m}^2+\text{sec}^2)^{0.5}$. For simplicity, the unit is denoted as “SI” here on.)

Moreover, the parameter for the linear term is 7.35SI, indicating that each additional insertion would increase the positive displacement by 7.12SI, given a constant number of exits. It is interesting to note that the estimated values of τ (=1.4sec) and d (=7m) yield a vector along the characteristic with a length of 7.14, which is close to the estimated parameter of the linear term, 7.12. This indicates that given a fixed number of exits, each additional insertion has an impact of simply adding a vehicle to the traffic stream and that no additional delay is incurred other than the delay by introducing a unit vehicle. Moreover, in light of the positive parameter of the intercept term (4.06), one can deduce that each additional exit has an impact less than subtracting a vehicle from the traffic stream. This may occur when a follower does not close a gap entirely and maintains a larger spacing upon his leader's departure from the lane. Thus, the results imply that for the same number of insertions and exits, we expect to observe additional delay to the traffic flow upstream compared to no LC (0 insertions, 0 exits) case.

Similar results were obtained for US 101 (see Figure 4(d) for a scatter plot and average by the net number), such that the estimated values of τ (=1.45sec) and d (=7.1m) yield a vector with a length of 7.25SI. This estimated value is similar to the estimated parameter of the linear term, 7.32. For US101, the

estimated parameter for the intercept term (15.7) is nearly twice as large as the linear term. This indicates that followers of exiting vehicles do not close their gaps at all. This seems highly unlikely as the freeway section is heavily congested. This seems attributable to a relatively large scatter, and a further investigation is warranted.

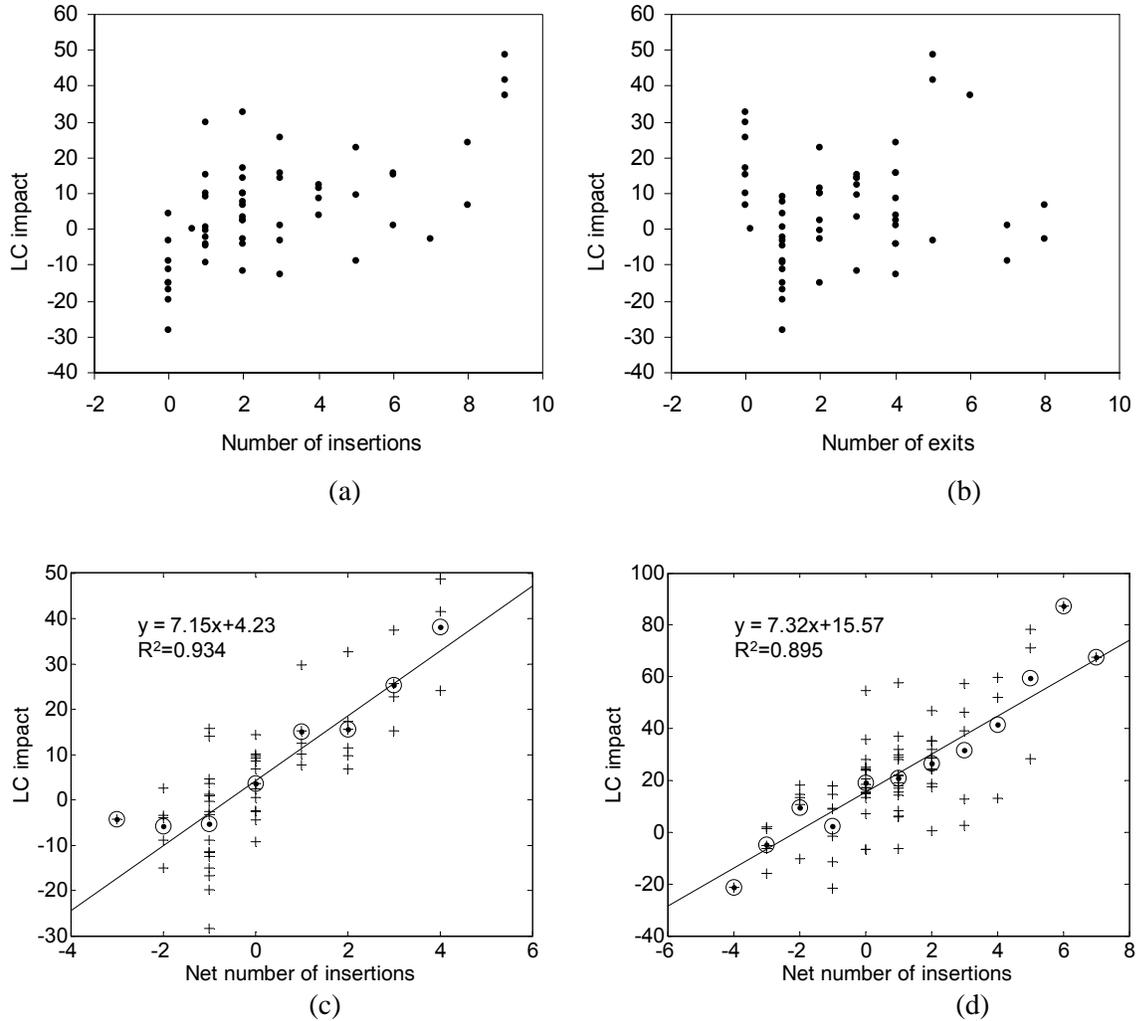


FIGURE 4

- (a) LC Impact vs. Number of Insertions, I-80
- (b) LC Impact vs. Number of Exits, I-80
- (c) LC Impact vs. Net Number of Insertions, I-80
- (d) LC Impact vs. Net Number of Insertions, US101

Note that regarding the errors made in this analysis we can make the following decomposition. The error can be related to:

- w : provided that we use 15 vehicles, we have an error of 2% on w (35).
- the NGSim longitudinal position's measurement, estimated to be 1.2 m (see www.ngsim.fhwa.dot.gov).

For both errors we can examine various types. If they are comparable to a white noise, their impact is negligible in the value of the regressions shown above (because we combine many observations in our

sample). If those errors are systematic, they do not induce any systematic biases in our measurements, since we are using spatial differences.

6. IMPACT RELATED TO OTHER VARIABLES

In addition to the numbers of insertions and exits, two other types of additional factors are considered: an average traffic state around LC maneuvers and perturbations in traffic states by lane changers (in region *b* of Figure 3(a)) at the time of maneuvers. The two factors are measured separately for insertions and exits in terms of speed and spacing. As illustrated in Figure 5, the average state is measured by taking the average speed of five preceding leaders along characteristics with respect to the time of each maneuver. The perturbation in traffic state is then taken as the difference between this average speed and the speed of the lane-changer at the time of the maneuver. Note that speeds here are 1-second moving averages since the trajectory data display some noise in its original form (36). For multiple maneuvers, the average state is the average of the individual measurements, and the perturbation in state is the sum of all individual perturbations. The traffic states and their perturbations are also measured in terms of spacing (see Figure 5(c)). Finally, the set of independent variables considered are listed below.

N_{in} : Number of insertions

N_{ex} : Number of exits

N_{net} : Net number of entries, $N_{entry} - N_{exit}$

v : Average 1-second moving average speed of lane changers at the time of maneuver

\bar{v} : Average speed of five preceding vehicles to lane-changer along characteristics, i.e.,

$$\bar{v} = \frac{1}{5} \sum_{i=1}^5 v_i$$

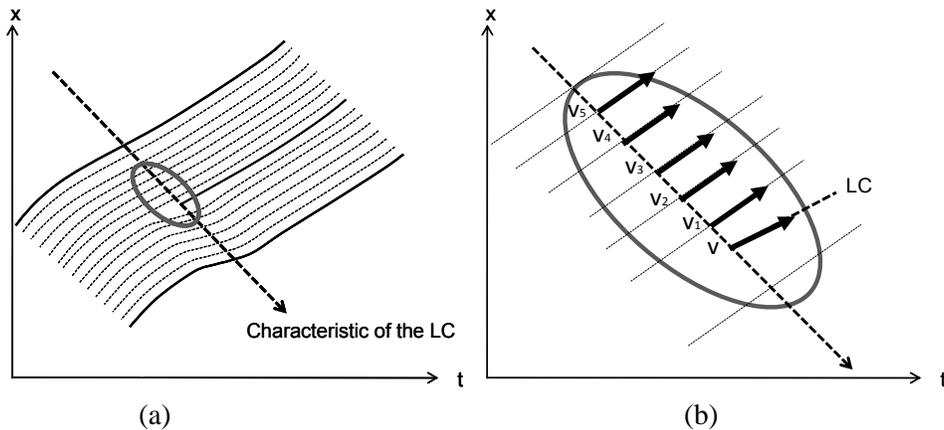
s : Average spacing of lane-changer at the time of maneuvers

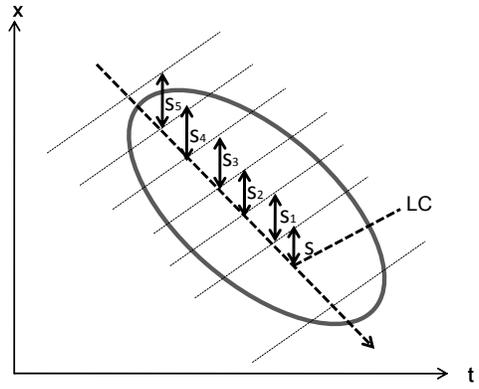
\bar{s} : Average spacing of five preceding vehicle to lane-changer (immediate follower for exiting maneuver) along characteristics, i.e.,

$$\bar{s} = \frac{1}{5} \sum_{i=1}^5 s_i$$

Δv : Perturbation in speed, $\bar{v} - v$

Δs : Perturbation in spacing, $\bar{s} - s$





(c)

FIGURE 5 Illustration of Measuring Average Traffic States around a LC Maneuver
 (a) An Example of an Insertion; (b) Measuring Average Speed around a LC Maneuver
 (c) Measuring Average Spacing around a LC Maneuver

The significance of each of these variables is evaluated by the Principal Components Analysis (PCA). The PCA is a statistical method that systematically looks for tendencies/correlations among variables (including a dependent variable) in a dataset. It finds a subset of variables (in a reduced dimensional space) that are orthogonal and best represent the data scatter. The results from the PCA are summarized in Table 2. The variables associated with correlations larger than 0.6 were considered to be significant factors (37). It confirms the preliminary observation in that the net number of insertions has the most significant effect on the magnitude of LC impact. This is consistent for both I-80 and US 101. It is also notable that the number of insertions is the second most correlated factor for I-80. This is attributed to the earlier observation that insertions have more predominant impact than exits. All other variables came out insignificant, which is rather surprising. It is speculated that this result is attributed to the small range of speeds (between 0 and 15 m/s) observed in the data sets. Nevertheless, this method of measuring average state and its perturbation can be easily applied to a larger dataset in the future.

TABLE 2 Correlation Coefficients Measured by Principal Components Analysis

Variable	Correlation Coefficient	
	I 80	US 101
N_{in}	0.62	0.34
N_{ex}	0.05	-0.35
N_{net}	0.80	0.72
v	0.20	0.04
\bar{v}	0.17	0.13
s	0.22	0.07
\bar{s}	0.48	0.13
Δv	-0.06	0.09
Δs	0.26	0.08

7. CONCLUSIONS

The present study is concerned with measuring the impact of lane-changing maneuvers and identifying significant factors. We have developed a methodology to measure the cumulative impact of insertions and exits within a set of fifteen vehicles. The methodology facilitates a simple car-following model of Newell (2002) to predict a virtual trajectory of the fifteenth vehicle based on the first leader. Thus, the methodology is fully consistent with the LWR kinematic-wave theory. The discrepancy between the actual trajectory and the simulated one along characteristic was measured as the net impact of insertions and exits.

Based on the methodology, we have analyzed the NGSIM trajectory data from I-80 and US101. The results show that the net number of insertions is the most significant factor in relation to the measured LC impact and that the impact of an insertion is larger than that of an exit. Traffic conditions around LC maneuvers and the perturbed state by lane-changers were also evaluated for significance. However, the PCA results show that the impact of LC is not highly correlated with state-related variables. As discussed previously, a small range of speed due to heavily-congested conditions seem to have an effect on the result. Thus, a proper treatment of traffic states will require a large range of speed, which will most likely necessitate a collection of extensive trajectory data. Furthermore, it would be desirable to obtain larger samples for more in-depth statistical analysis of various variables. For this, it would be interesting to see if the assumption of a constant wave propagation speed holds for vehicles less than 15, which may result in larger samples.

Finally, relatively small samples of LC impacts were measured from the two freeway datasets. Thus, it was not possible to conduct a more detailed analysis of the incremental effect of insertions and exits as well as comparisons between the two types of maneuvers. Nevertheless, this study provides a methodology that is theoretically grounded and can be verified easily from data.

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