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Driver mandatory lane change behavior: Use of governing gap in critical gap estimation

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DRIVER MANDATORY LANE CHANGE BEHAVIOR: USE OF GOVERNING GAP IN CRITICAL GAP ESTIMATION

by

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ABSTRACT

This study analyzed the driver gap acceptance and rejection behavior during mandatory lane changes on a multilane freeway in congested and uncongested traffic conditions. During a lane change, drivers were more receptive to either the leading or the trailing gaps with vehicles in the target lane which governed the drivers' lane change and is termed as the governing gap. Drivers maneuvered till the governing gap was greater than the critical gap, accepted the gap and made a lane change. In this process, drivers reduced the non-governing gap to increase the length of the governing gap. The drivers as a result were found to be consistent with respect to the governing gap and inconsistent with respect to the non-governing gap. The governing gap, therefore, addresses the consistent driver behavior and avoids categorization of drivers as inconsistent. Critical gaps were estimated based on the consistent driver behavior using accepted and LRLA gaps, firstly, by categorizing the drivers based on the governing gap and the type of maneuver, and secondly, by categorizing the drivers based on the relative speeds. For a simple lane change model, categorization by governing gap and type of maneuver will be sufficient with a critical gap value distribution defined by empirical data for congested and uncongested traffic conditions. For a sophisticated lane change model, in addition to maneuver types, critical gaps estimated based on difference in relative speeds will help better replicate the realistic lane change behavior of drivers in case of congested traffic conditions.

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DRIVER MANDATORY LANE CHANGE BEHAVIOR: USE OF GOVERNING GAP IN CRITICAL GAP ESTIMATION

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ABSTRACT

This study analyzed the driver gap acceptance and rejection behavior during mandatory lane changes on a multilane freeway in congested and uncongested traffic conditions. During a lane change, drivers were more receptive to either the leading or the trailing gaps with vehicles in the target lane which governed the drivers' lane change and is termed as the governing gap. Drivers maneuvered till the governing gap was greater than the critical gap, then accepted the gap and made a lane change. In this process, drivers reduced the non-governing gap to increase the length of the governing gap. The drivers, as a result, were found to be consistent with respect to the governing gap and inconsistent with respect to the non-governing gap. The governing gap, therefore, addresses the consistent driver behavior and avoids categorization of drivers as inconsistent. Critical gaps were estimated based on consistent driver behavior using the accepted and LRLA gaps, firstly, by categorizing the drivers based on the governing gap and the type of maneuver, and secondly, by categorizing the drivers based on the relative speeds. For a simple lane change model, categorization by governing gap and type of maneuver will be sufficient with a critical gap value distribution defined by empirical data for congested and uncongested traffic conditions. For a sophisticated lane change model, in addition to maneuver types, critical gaps estimated based on difference in relative speeds will help better replicate the realistic lane change behavior of drivers in case of congested traffic conditions.

1. INTRODUCTION

Gap acceptance is an important element of lane-change algorithms used in microscopic traffic simulation models. To execute a lane change, drivers' assess the positions and speeds of the leading and trailing vehicles in the target lane, and evaluate whether the leading and trailing gaps are sufficient by comparing it with a minimum value i.e., a critical gap. This behavior was investigated by analyzing leading and trailing gaps individually and critical gaps were estimated using accepted and maximum rejected gaps (*1*). A large number of drivers, however, were observed to behave inconsistently and were not considered in the analysis. In a subsequent paper, both the trailing and leading gaps for pair of vehicles (assumed leader and subject vehicle, assumed follower and subject vehicle) were analyzed to estimate the critical gaps (*2*). The percentage of inconsistent drivers reduced by considering different rejected gaps; the mean rejected, median rejected, and the largest rejected less than the accepted (LRLA) gaps. These papers, however, did not analyze the inconsistent driver behavior, which limited the data to a typical type of lane change behavior. This paper examined the driver behavior by plotting trajectories of vehicles and found that the drivers behaved consistently with either the leading or the trailing gaps, and inconsistently with the other gap. The gap with which the drivers behaved consistently was found to govern the lane change and therefore, in this paper is termed as the governing gap. Using the governing gap, critical gaps were estimated and the results, thus obtained, represent the realistic driver lane change behavior. Table 1 presents the terminologies used in this paper.

Gap acceptance was modeled earlier in various ways (*3-7*) to represent the lane change behavior of drivers. Gap acceptance models are formulated as binary choice problems in which drivers decide whether to accept or reject the available gap by comparing it with the critical gap (e.g. *8-10*). Critical gaps are defined as the minimum time, in seconds, between successive vehicles in which the subject vehicle can perform the intended maneuver. Critical gaps were modeled as random variables and different distributions have been proposed to capture the variation in the behaviors of different drivers and for the same driver over time. Herman and Weiss (*11*) assumed an exponential distribution, Drew et al. (*12*) assumed a log-normal distribution, Miller (*13*) assumed a normal distribution, etc. Similarly, lane change models in simulation software such as CORSIM (*14*), SITRAS (*15*), MITSIM (*16*), VISSIM (*17*), etc. use critical gaps in different ways.

In this paper, critical gaps are estimated for different types of drivers, categorized based on the (a) governing gap and type of maneuver, and (b) relative speeds of subject vehicle with respect to the target lane vehicles, to analyze the driver lane change behavior. Furthermore, the effect of lane change location on gap acceptance was examined over a weaving section where two mandatory lane change movements take place i.e., vehicles weave-in and weave-out of the section. The effect of the type of movement on the accepted gap was also examined.

This paper is organized as follows: field data is presented next followed by data analysis. Methodology, analysis and discussion of results, is presented in the third and fourth sections of the paper. The paper ends with conclusions and recommendations for future research.

TABLE 1 Terminologies Used in the Paper

- Adjacent lane: the next lane to the left of the shoulder lane (Figure 1).
- Assumed follower: the immediate follower to the subject vehicle in the target lane.
- Assumed leader: the immediate leader to the subject vehicle in the target lane.
- Consistent driver: a driver who rejects gaps those are smaller than the accepted gap.
- Adjacent lane: the next lane to the left of the shoulder lane (Figure 1).
- Assumed follower: the immediate follower to the subject vehicle in the target lane.
- Assumed leader: the immediate leader to the subject vehicle in the target lane.
- Consistent driver: a driver who rejects gaps those are smaller than the accepted gap.
- Inconsistent driver: a driver who rejects gaps those are larger than the accepted gap.
- Leading accepted gap: the time gap between the subject vehicle and the assumed leader at the time frame when the center of the front bumper of the subject vehicle just crosses the lane marking. Crossing the lane marking is confirmed by the change in the lane identification attribute of the subject vehicle in the given data.
- Leading time gaps: Calculated as the distance between the rear bumper of the assumed leader and the front bumper of the subject vehicle over the speed of the subject vehicle.
- Mandatory lane changes: the essential lane change that drivers make to exit from the off-ramp, enter main lanes from the on-ramp, or merge to the adjacent lane to avoid lane drop.
- Rejected leading gap: the largest time gap less than the accepted gap between the subject vehicle and the assumed leader within the time frame the subject vehicle was with the same assumed leader prior to the lane change.
- Rejected trailing gap: the largest time gap less than the accepted gap between the subject vehicle and the assumed follower within the time frame the subject vehicle was with the same assumed follower prior to the lane change. In this paper, rejected gap means the largest rejected less than the accepted gap.
- Shoulder lane: the rightmost lane (Figure 1).
- Subject vehicle: the vehicle that is making a lane change. Also referred as the lane changer.
- Trailing accepted gap: the time gap between the subject vehicle and the assumed follower at time step when the center of the front bumper of the subject vehicle just crosses the lane marking.

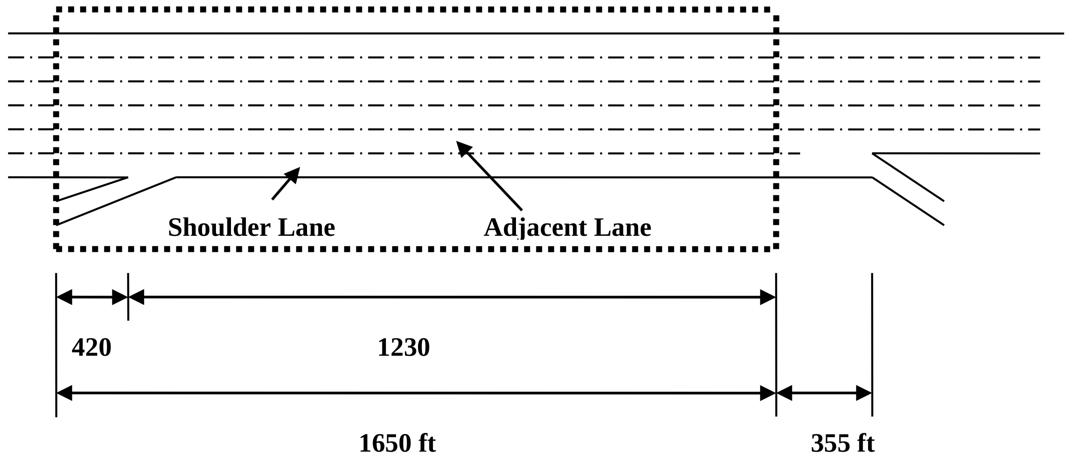
TABLE 1 Terminologies Used in the Paper (cont.)

- Trailing time gaps: calculated as the distance between the rear bumper of the subject vehicle to the front bumper of the assumed follower over the speed of the assumed follower.

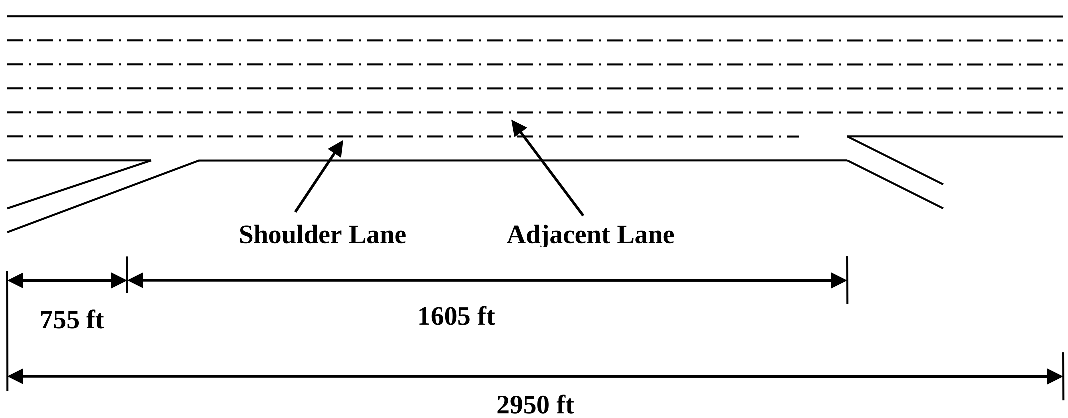
2. FIELD DATASET

This study utilizes NGSIM data (*18*) collected at a weaving section on I-80 in Emeryville, California (site schematic presented in Figure 1), during congested traffic conditions from 04:00 to 04:15 p.m. and 5:00 to 5:30 p.m. and during uncongested traffic conditions from 2:35 to 3:05 p.m. in April, 2004. Traffic flow in this data ranged from 600 to 1940 vehicles/hour/lane and traffic densities ranged from 21 to 135 vehicles/mile. The data consist of positions of all the vehicles collected at every 1/10th and 1/15th of a second in congested and uncongested traffic conditions respectively.

The raw dataset was refined per the analysis required for this paper. Vehicles travelling at velocities less than 1 ft/s were not considered as they were of little help in computing the critical gap. Further, mandatory lane change movements; adjacent lane to the shoulder lane to exit the highway from the off-ramp, and from the shoulder lane to the adjacent lane movement to merge with the main highway lanes, were analyzed in this paper. In addition, only lane changers in interaction i.e., separated by 250 feet or less (*19*, *20*) with both the leading and the trailing vehicles during a lane change were considered. Further, to quantify interaction between vehicles in terms of time gap, the leading and trailing time gaps less than or equal to five seconds were used to analyze the data. For homogeneity in driver behavior, only passenger vehicles in the data were considered for analysis.



(a) Congested data collected site with Six Main Lanes and an On-Ramp
(Data collected in the dotted area)



(b) Uncongested data collected site with Six Main Lanes, an On-Ramp and an Off-Ramp

Figure 1 Schematic of data site at I-80, Emeryville, California
(Note: Figure not to scale)

3. DATA ANALYSIS: EXAMINING DRIVER BEHAVIOR

To examine the driver behavior, trajectories of the subject vehicle, the leading vehicle and the following vehicle in interaction before and to the point of a lane change were plotted. Figure 2 presents a sample of these trajectory plots; y-axis indicates the position of the vehicles and x-axis indicates the time frames at every half-second. At the start of the plot, the subject vehicle was in its ‘current’ lane and the leading and trailing vehicles were in the ‘target’ lane. The subject vehicle maneuvered and moved into the target lane between the leading and following vehicles. The time frame, where the trajectories end, represents the point in time when the subject vehicle accepted the gap. It can be observed that the subject vehicle interacted closely with either the leader or the follower at the start of the plots. If the subject vehicle closely interacted with the leading vehicle before a lane change then the governing gap was the leading gap and if the subject vehicle closely interacted with the trailing vehicle before a lane change then the trailing gap was the governing gap.

Initially, when the subject vehicle attempted a lane change, the governing gap available was shorter but the non-governing gap was larger than the critical gap. The subject vehicle maneuvered and increased the governing gap higher than the critical gap by reducing the non-governing gap and made a lane change. Hence, the governing gap influenced the driver lane change behavior and is further analyzed in the paper. Drivers behaved inconsistently with the non-governing gap as the subject vehicle reduced the available (inconsistent) gap at the beginning of the trajectory and in the end accepted a shorter gap. In fact, the subject vehicle was increasing the governing gap and reducing the non-governing gap. Based on the trajectory of the vehicles and the type of leading or trailing governing gaps, different types of driver maneuvers were observed. These maneuvers were categorized into four types and the accepted and rejected gaps were computed for each type. The maneuver types follow and the accepted and rejected gaps are discussed later in this section.

3.1. Maneuver Types

3.1.1. Maneuver Type 1: Subject Vehicle Decelerates to Move behind the Assumed Leader

Presented in Figure 2(a), the leading gap is the governing gap, as the subject vehicle closely interacts with the assumed leader in the target lane, and the trailing gap is the non-governing gap. Initially, the subject vehicle was ahead of the assumed leader in the target lane and the subject vehicle slowed down in its current lane to maneuver behind the assumed leader and then made a lane change. In the process, the subject vehicle increased the leading governing gap by reducing the trailing non-governing gap. The subject vehicle moved from its current lane to the target lane whereas the assumed leader and assumed follower continued in the target lane. As the subject vehicle decelerated to move behind the leading vehicle, the trajectories of those vehicles intersected.

3.1.2. Maneuver Type 2: Subject Vehicle Accelerates to Move In Front of the Assumed Follower

Presented in Figure 2(b), the trailing gap is the governing gap as the subject vehicle interacts with the assumed follower in the target lane. Initially, the subject vehicle was behind the assumed follower in the target lane with trailing governing gap less than the critical gap. The subject vehicle accelerated past the assumed follower to increase the governing gap and made a lane change by reducing the non-governing leading gap. The trajectories of the subject vehicle and the assumed follower intersected as the subject vehicle passed the assumed follower in the target lane.

3.1.3. Maneuver Type 3: Subject Vehicle Decelerates to Move between the Assumed Leader and the Assumed Follower

Presented in Figure 2(c), the leading gap is the governing gap as the subject vehicle interacts with the assumed leader. The subject vehicle moves from the current lane to the target lane in between the assumed follower and assumed leader during the lane change. Initially, the leading gap, which is the governing gap, was not sufficient for the subject vehicle to change lanes. As the subject vehicle traveled along the weaving section, it increased the leading gap and made a lane change when the gap was sufficient. In the process, the available non-governing trailing gap was utilized by the subject vehicle but as the trailing vehicle was sufficiently behind, the safety of the lane change was assured.

3.1.4. Maneuver Type 4: Subject Vehicle Accelerates to Move between the Assumed Leader and the Assumed Follower

Presented in Figure 2(d), the trailing gap is the governing gap. Similar to Type 3, the subject vehicle moves from the current lane to the target lane in between the assumed follower and the assumed leader during the lane change. The trailing governing gap available for the subject vehicle initially was not sufficient to make a lane change. The subject vehicle traveled along the weaving section to lengthen the trailing gap by reducing the non-governing leading gap and made a lane change when the governing gap was sufficient. In maneuvers 3 and 4, the trajectories do not intersect as the subject vehicle did not pass the target lane assumed leader or the assumed follower.

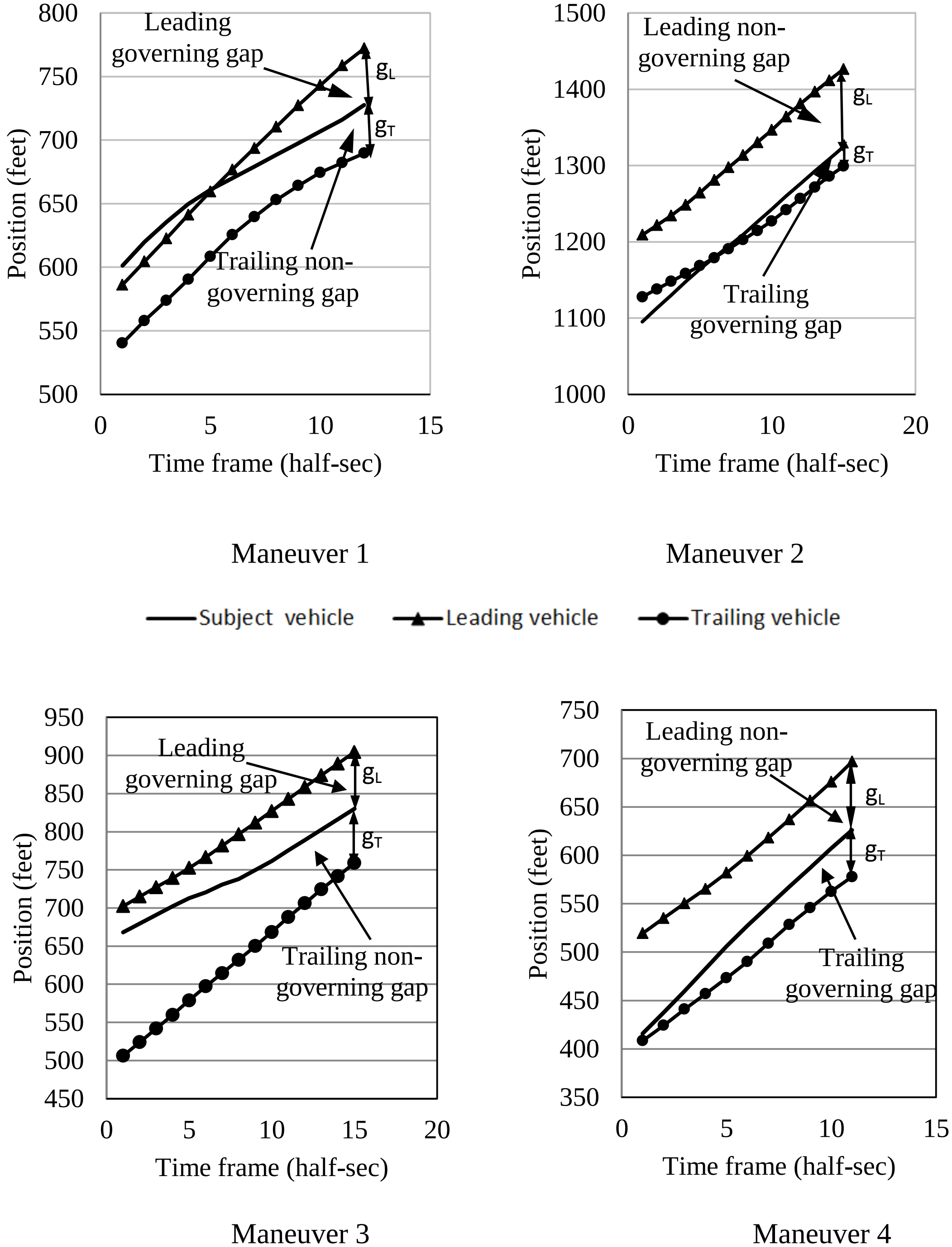


Figure 2 Different types of driver maneuvers

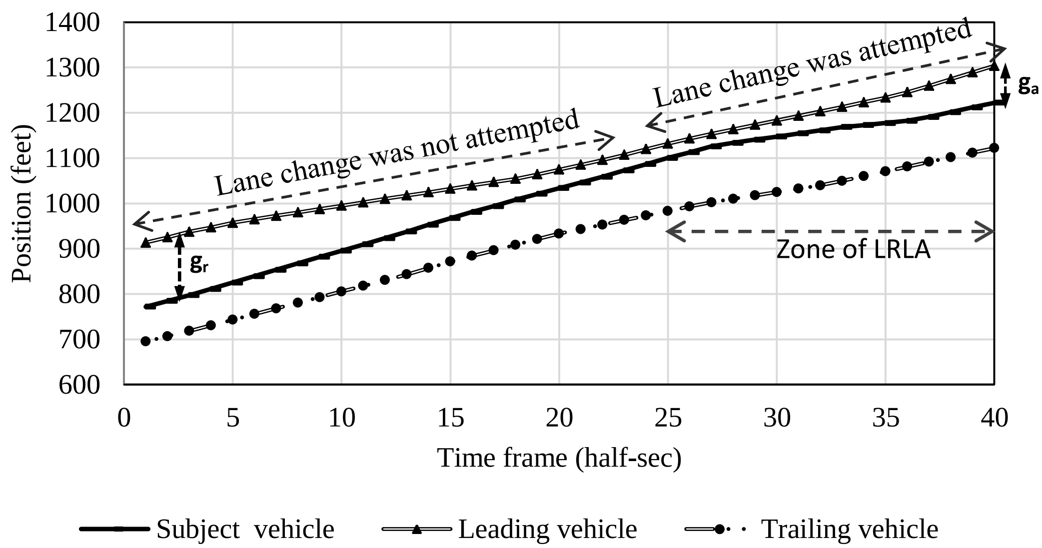
3.2. Accepted and Rejected Gaps

At the instant a gap was accepted, gaps rejected by the subject vehicle were determined for every half-second. The number of rejected gaps depended upon the time taken by the subject vehicle to make a lane change. A number of drivers took very little time to make a lane change, some as soon as they left the on-ramp, and a number of drivers took up to twenty seconds to make a lane change. Only, drivers that had a minimum of five rejected gaps (2.5 seconds) were analyzed for this paper. This duration of time was chosen under the assumption that a lane change behavior can be realistically observed if the driver spends at least three seconds after leaving the on-ramp.

If the subject vehicle passed one or more vehicles in the target lane then the last pair of leader and follower just before the subject vehicle changed lanes were considered as the assumed leader and assumed follower for a lane change. Rejected gaps with respect to these vehicles were only considered. In addition, an equal number of rejected gaps for trailing and leading were considered to ensure that both the assumed leader and assumed follower were in interaction with the subject vehicle at the same time.

3.2.1. Largest Rejected Less than the Accepted (LRLA) gap

A gap (g_r) larger than the accepted gap (g_a), as indicated in Figure 3, was rejected by the driver at the time when the driver was not attempting a lane change (designated in the plot). Unlike unsignalized intersections, where a driver comes to a complete stop before entering the major street, on freeways, a driver seeks a suitable gap while in motion and several gaps are rejected before a gap is accepted. Therefore, considering an appropriate value for the rejected gap is important to obtain an estimate of a critical gap that represents realistic driver lane change behavior. A mean or a median rejected gap could lead to under estimation of critical gaps (*21*). The largest rejected gap less than the accepted gap (LRLA) allows for realistic estimation of critical gaps. This estimation assumes that all rejected gaps for consistent drivers are less than the corresponding accepted gap. This also eliminates any inconsistent driver behavior and retains drivers as consistent.



g_r – rejected gap g_a – accepted gap

Figure 3 Trajectory of a driver: Need for LRLA

4. METHODOLOGY

This paper analyzes driver gap acceptance and rejection behavior using detailed vehicle trajectory data and proposes critical gap distributions that can be utilized in modeling realistic mandatory lane change behavior of drivers in microscopic simulation models. Lane changers were identified from the data; each driver had an accepted and a LRLA gap. Both the accepted and LRLA gaps were fitted various distributions. Goodness-of-fit tests namely Anderson-Darling (AD) and Kolmogorov-Smirnov (KS) normality test were performed. Using the accepted and the LRLA gaps, critical gaps were estimated by the maximum likelihood estimation (MLE) method. The use of MLE method has been recommended in earlier papers (*1*, *22*).

4.1. Distribution Fitting

Several distributions were tried to fit the accepted and LRLA gaps using probability plots in Minitab. A probability plot performs a similar function as an empirical cumulative distribution function (CDF) plot. The CDF and associated confidence intervals were determined based on the distribution parameters estimated using the field data. If the distribution fitted the data, then the plotted points will fall close to the fitted distribution line and will be within the confidence intervals.

4.2. Goodness-of-Fit Tests

The AD-test was performed to ensure the selection of distribution that best fits the data set. Further, KS-normality test was performed to verify the normality of the data and the goodness-of-fit of distributions to the data as only few drivers were found for some type of maneuvers.

4.2.1. Anderson-Darling Test

Minitab performed the AD goodness-of-fit test besides fitting the probability plots to the data. The best distribution fit was selected based on the AD-statistic and an associated p-value obtained from the test. If the AD-statistic was small and the associated p-value was larger than the significance level chosen, then the data are said to follow a particular distribution.

4.2.2. Kolmogorov-Smirnov Normality Test

KS-Normality test compares the empirical cumulative distribution function (CDF) of the data with the expected normal distribution. A hypothesis test was performed to examine whether or not the observations follow a normal distribution. A p-value from the KS-test was used to check if the data followed a normal distribution. If the p-value was greater than the chosen significance level, then the data are said to follow the normal distribution. For additional information on the distribution fitting and goodness of fit tests, the reader is referred to (*23*).

4.3. Critical Gap Estimation

Critical (time) gap distributions are used to model the realistic lane change behavior of drivers in simulation models. Several methods (both deterministic and stochastic) have been used and evaluated in the literature for estimating critical gaps (*13*, *1*). Maximum likelihood estimation (MLE) was recommended for use as the distribution parameters can be estimated (*1*). Therefore, it was used in this paper to estimate the critical gaps using the methodology proposed in (*22*).

When using MLE, the gap acceptance process is treated as a binary function with accepted gaps represented as one and rejected gaps represented as zero. For a freeway, it is assumed that observations of ‘n’ drivers have been made and the observations for each include the accepted gap, ‘a_i’ and the rejected gap, ‘b_i’. The likelihood of a sample of ‘n’ drivers is expressed as:

$$\prod_{i=1}^{n}[F(a_i)-F(b_i)] \qquad (1)$$

where F is the cumulative distribution of gaps, F(a_i) is the probability that a gap ‘a_i’ will be accepted, and F(b_i) is the probability that a gap ‘b_i’ will be rejected by a randomly selected driver. This likelihood function (Equation 1) was maximized to determine the critical gap. Further, MLEs for accepted and rejected gaps were computed to compare with the critical gaps estimated to ensure consistent driver behavior. The formulae used to compute the MLEs were:

$$\text{Mean } (\mu) = \frac{\sum_{i=1}^{n}\ln X_i}{n} \qquad (2)$$

$$\text{Standard deviation } (\sigma) = \left(\frac{\sum_{i=1}^{n}(\ln X_i-\mu)^2}{n}\right)^{1/2} \qquad (3)$$

where ‘X_i’ is the time gap (accepted or rejected), ‘n’ is number of drivers, μ is the likelihood mean, and σ is the likelihood standard deviation. For additional information on the maximum likelihood estimates, the reader is referred to (*24*).

5. RESULTS: ANALYSIS AND DISCUSSION

One hundred and twenty eight lane changes in congested conditions and 196 lane changes in uncongested conditions met the selection criteria from the NGSIM data. In congested conditions, 95 lane changes were observed from the shoulder lane to the adjacent lane and the remaining 33 from the adjacent lane to the shoulder lane. In uncongested conditions, 154 lane changes were observed from the shoulder lane to the adjacent lane and the remaining 42 from the adjacent lane to the shoulder lane. Maneuvers in each movement were categorized into four types as explained earlier in the paper. Accepted and LRLA gaps for each driver in all maneuvers were computed.

5.1. Distribution Fitting

Several distributions such as gamma, normal, lognormal, exponential, and weibull were fitted to both the accepted and LRLA gaps in congested as well as uncongested traffic conditions. For lognormal distribution, the value of AD-statistic obtained was small from probability plots and the corresponding p-values were greater than 0.05 ($p > .05$). Tables 2 and 3 present the results of lognormal distributions fitted to both the accepted and LRLA gaps for congested and uncongested traffic conditions, respectively. From the KS-normality test, the p-value was also observed to be greater than 0.05 ($p > .05$). Therefore, the tests failed to reject the null hypothesis that the given data follow lognormal distribution at 95% level of significance. Hence, the lognormal distribution fitted both the accepted and rejected gaps for all maneuvers in both congested and uncongested traffic conditions.

TABLE 2 Results of Goodness of Fit Tests for Lognormal Distribution for Congested Traffic Conditions

Anderson-Darling Goodness of Fit Test					
Maneuver type	**Gap type**	**Shoulder lane to Adjacent lane movement**		**Adjacent lane to Shoulder lane movement**	
		AD-statistic	**p-value***	**AD-statistic**	**p-value***
1	Accepted	0.295	0.585	0.374	0.374
	LRLA	0.191	0.893	0.534	0.144
2	Accepted	0.389	0.363	0.315	0.484
	LRLA	0.573	0.125	0.276	0.574
3	Accepted	0.240	0.743	0.189	0.796
	LRLA	0.267	0.649	0.250	0.555
4	Accepted	0.316	0.512	0.250	0.227
	LRLA	0.212	0.829	0.250	0.227
Kolmogorov-Smirnov Normality Test					
Maneuver type	**Gap type**	**Shoulder lane to Adjacent lane movement**		**Adjacent lane to Shoulder lane movement**	
		KS-statistic	**p-value***	**KS-statistic**	**p-value***
1	Accepted	0.091	>0.150	0.138	>0.150
	LRLA	0.075	>0.150	0.204	0.076
2	Accepted	0.101	>0.150	0.195	>0.150
	LRLA	0.118	>0.150	0.170	>0.150
3	Accepted	0.168	>0.150	0.188	>0.150
	LRLA	0.132	>0.150	0.254	>0.150
4	Accepted	0.116	>0.150	0.260	>0.150
	LRLA	0.120	>0.150	0.260	>0.150

** Distribution fits the data if p>.05 (significance level)*

TABLE 3 Results of Goodness of Fit Tests for Lognormal Distribution for Uncongested Traffic Conditions

Anderson-Darling Goodness of Fit Test					
Maneuver type	**Gap type**	**Shoulder lane to Adjacent lane movement**		**Shoulder lane to Adjacent lane movement**	
		AD-statistic	**p-value***	**AD-statistic**	**p-value***
1	Accepted	0.648	0.079	0.358	0.384
	LRLA	0.681	0.070	0.288	0.549
2	Accepted	0.276	0.605	0.519	0.145
	LRLA	0.308	0.521	0.353	0.397
3	Accepted	0.522	0.176	0.156	0.928
	LRLA	0.516	0.182	0.142	0.952
4	Accepted	0.540	0.152	0.173	0.903
	LRLA	0.443	0.267	0.232	0.737
Kolmogorov-Smirnov Normality Test					
Maneuver type	**Gap type**	**Shoulder lane to Adjacent lane movement**		**Adjacent lane to Shoulder lane movement**	
		KS-statistic	**p-value***	**KS-statistic**	**p-value***
1	Accepted	0.102	0.119	0.190	>0.150
	LRLA	0.114	0.081	0.170	>0.150
2	Accepted	0.117	>0.150	0.207	>0.150
	LRLA	0.125	>0.150	0.153	>0.150
3	Accepted	0.093	>0.150	0.121	>0.150
	LRLA	0.105	>0.150	0.121	>0.150
4	Accepted	0.148	0.099	0.104	>0.150
	LRLA	0.139	>0.150	0.119	>0.150

**Distribution fits the data if p>.05 (significance level)*

5.2. Congested Traffic Conditions

5.2.1. Accepted and Rejected Gaps

Table 4 presents the summary statistics of the accepted and rejected gaps for the four maneuvers in congested traffic conditions. In the shoulder-to-adjacent movement, the mean of the accepted and LRLA gaps in all maneuvers ranged from 1.090 to 1.204 seconds and 0.942 to 1.135 seconds, respectively with a standard deviation varying from 0.487 to 0.647 second and 0.492 to 0.619 second, respectively. In the adjacent-to-shoulder movement, the mean accepted gaps in maneuvers 1 and 2 were 1.081 and 1.113 seconds, respectively with a standard deviation of 0.573 and 0.585, respectively and LRLA gaps in maneuvers 1 and 2 were 0.937 and 0.983 second, respectively with a standard deviation of 0.520 and 0.489 second, respectively.

In shoulder lane to adjacent lane movement, maneuvers 1 and 2 comprised of about 70% of drivers. In these maneuvers, drivers either accelerated or decelerated to pass the target lane vehicle and made a lane change. This behavior can be stated as more attentive to make a lane change. These drivers accepted (mean values) slightly shorter gaps (1.090 and 1.137 seconds) compared to drivers in maneuvers 3 and 4 (1.204 and 1.144 seconds). In maneuvers 3 and 4, the drivers were not aggressive; they did not move past the target lane vehicle, rather maneuvered between the assumed leader and assumed follower to make a lane change. As a result, these drivers accepted slightly larger gaps. Further, the data indicated more uniform driver behavior in accepting gaps in maneuvers 3 and 4 when compared to other maneuvers. This behavior can be noticed by observing the standard deviation of accepted gaps. The values of standard deviation in maneuvers 3 and 4 for accepted and rejected gaps (0.487, 0.492 sec and 0.629, 0.557 sec, respectively) showed lesser variation when compared to maneuvers 1 and 2 (0.647, 0.619 sec and 0.642, 0.590 sec, respectively).

Further, the accepted gaps were affected by the location of lane change. As expected, drivers accepted shorter gaps as they approached the off-ramp. Drivers indicated urgency to make a lane change and it increased as they approached the off-ramp. This phenomenon was observed in both the movements. This finding was consistent with Kita (*25*). Kita observed this behavior at an on-ramp and this paper observed at an off-ramp. Figure 4(a) represents the variation of accepted gaps along the weaving section for both the movements.

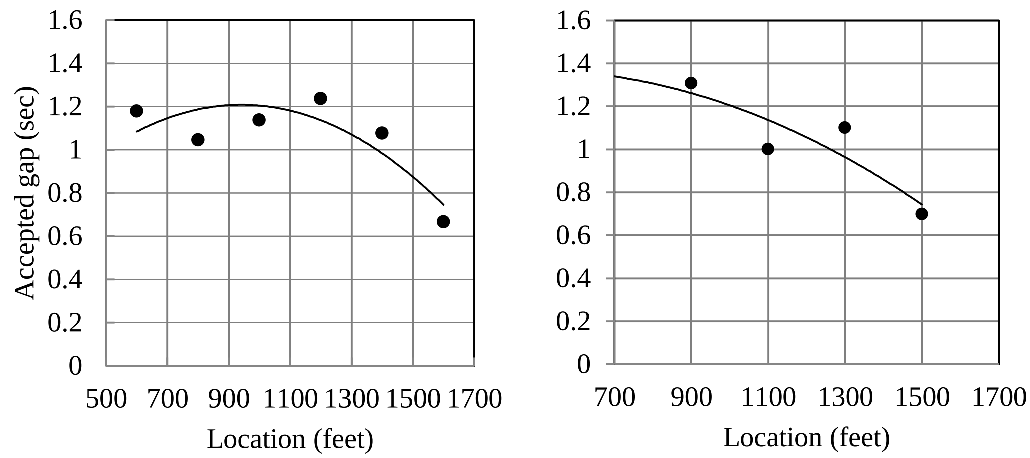
TABLE 4 Summary Statistics for Accepted, LRLA and Critical Gaps based on Maneuver Type in Congested Traffic Conditions

Shoulder lane to Adjacent lane movement								
Maneuver type	**1**		**2**		**3**		**4**	
Governing gap	**Leading**		**Trailing**		**Leading**		**Trailing**	
Gap type	**Accepted**	**LRLA**	**Accepted**	**LRLA**	**Accepted**	**LRLA**	**Accepted**	**LRLA**
No. of Lane Changes	46	46	21	21	13	13	15	15
Mean	1.090	0.942	1.137	1.001	1.204	1.135	1.144	1.061
Median	0.915	0.845	1.088	0.911	1.016	0.935	1.118	0.976
St. Dev.	0.642	0.590	0.647	0.619	0.629	0.557	0.487	0.492
Maximum	2.605	2.533	2.472	2.387	2.326	2.166	2.120	2.059
Minimum	0.208	0.170	0.271	0.176	0.512	0.496	0.334	0.327
Lognormal MLE's								
Mean	0.998	0.932	1.017	0.957	1.054	1.030	1.040	1.003
St. Dev.	0.266	0.272	0.294	0.308	0.238	0.224	0.215	0.216
Critical gap								
Mean	0.964		0.985		1.040		1.020	
St. Dev.	0.261		0.289		0.221		0.207	
Adjacent lane to Shoulder lane movement								
Maneuver type	**1**		**2**		**3**		**4**	
Governing gap	**Leading**		**Trailing**		**Leading**		**Trailing**	
Gap type	**Accepted**	**LRLA**	**Accepted**	**LRLA**	**Accepted**	**LRLA**	**Accepted**	**LRLA**
No. of Lane Changes	16	16	10	10	5	5	2	2
Mean	1.081	0.937	1.113	0.983	0.701	0.581	2.050	2.031
Median	1.035	0.944	1.025	0.932	0.672	0.646	2.050	2.031
St. Dev.	0.573	0.520	0.585	0.489	0.372	0.292	2.121	2.110
Maximum	2.167	2.007	2.578	2.137	1.305	0.977	3.549	3.523
Minimum	0.238	0.184	0.425	0.329	0.341	0.236	0.550	0.539
Lognormal MLE's								
Mean	1.002	0.938	1.023	0.970	0.839	0.774	1.362	1.357
St. Dev.	0.280	0.285	0.213	0.211	0.188	0.194	0.849	0.852
Critical gap								
Mean	0.966		0.994		-*		-*	
St. Dev.	0.269		0.197		-*		-*	

**critical gaps were not estimated as there were very few drivers in that category*

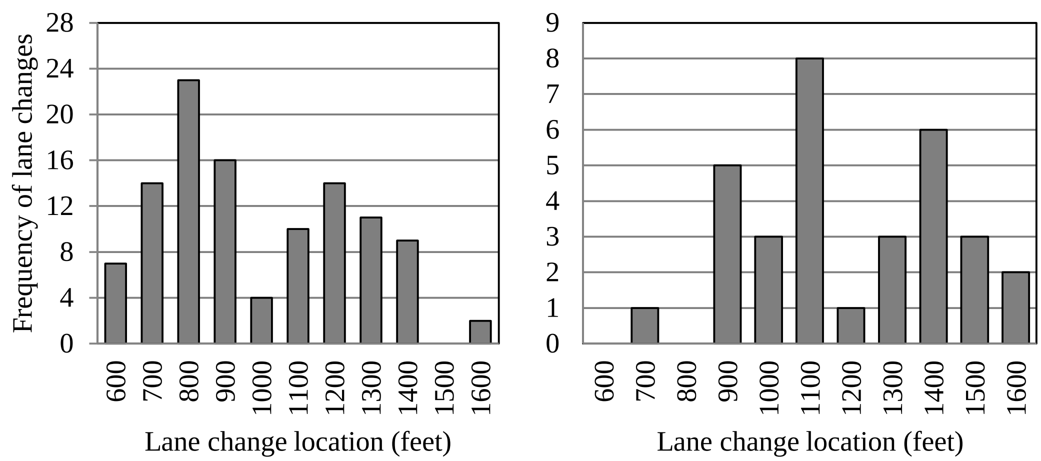
The mean accepted and LRLA gaps in the shoulder lane to the adjacent lane movement (1.090 and 0.942 seconds, respectively in maneuver 1 and 1.137 and 1.001 seconds, respectively in maneuver 2) were slightly larger when compared to the adjacent lane to the shoulder lane movement (1.081 and 0.937 seconds, respectively in maneuver 1 and 1.113 and 0.983 seconds, respectively in maneuver 2). This behavior was because the number of drivers, who accepted shorter gaps as they approached the off-ramp, was large in adjacent-to-shoulder movement when compared to shoulder-to-adjacent movement.

To closely study the variation in lane change frequency, the weaving section can be divided into three equal parts. The frequency of shoulder-to-adjacent lane changes was high in the first one-third (51%), and moderate in the second one-third (42%). The frequency of adjacent-to-shoulder lane changes was high in the second one-third (58%) and moderate in the last one-third (36%) of the weaving section. Figure 4(b) presents the variation in the frequency of lane changes over the length of the weaving section for both the movements. This lane change frequency was also observed previously on a two lane weaving section on I-95 NB, Washington, D.C. (*26*, *27*). As a result, the length of the weaving section available for the adjacent-to-shoulder lane changers was shorter and closer to the off-ramp. The drivers in the adjacent lane, therefore, accepted shorter gaps to make a lane change. This behavior is evident from Figure 4(a)(ii); shorter accepted gaps over the length of the weaving section.



(i) Shoulder to Adjacent movement (ii) Adjacent to Shoulder movement

(a) Variation of accepted gap along the length of the weaving section



(i) Shoulder to Adjacent movement (ii) Adjacent to Shoulder movement

(b) Variation of frequency of lane changes along the weaving section based on type of movement

Figure 4 Relationship between the merge location, frequency of lane changes and accepted gaps based on the type of movement in congested traffic conditions

5.2.2. Critical Gaps

Critical gaps were estimated using accepted and LRLA gaps. Since, accepted and LRLA gaps followed lognormal distribution, critical gaps were assumed to follow a lognormal distribution. Table 4 presents the critical gaps and MLEs for accepted and LRLA gaps for different types of maneuvers. For consistent driver behavior, critical gaps should be greater than LRLA gaps and smaller than the accepted gaps. It can be observed that the mean values of critical gaps fall between the mean values of accepted and LRLA gaps. Therefore, consistent driver behavior was observed.

5.2.2.1. Types of Maneuvers

The mean value of the estimated critical gaps for the different maneuvers varied from 0.964 to 1.040 seconds with standard deviation varying from 0.207 to 0.289 second. Difference in the mean value of critical gaps was not significant between different maneuvers of the same movement and between the different movements as well. This was established using the Delta method for confidence intervals (*28*).

Although different drivers adopted different maneuvers in changing lanes, the variation in accepted gaps of most of the drivers was found to be small. For most of the drivers (67%), the accepted gap ranged from 0.5 to 1.7 seconds. The mean value of the mean critical gaps estimated was about 1.002 second with a standard deviation of about 0.244 second. Most of the drivers were attentive in making a lane change and the variation in accepted gaps was not noticeable. Besides these drivers, few drivers accepted very short gaps (less than 0.5 sec, 12%) and very large gaps (greater than 1.7 sec, 20%, 17 drivers). Drivers who accepted very short gaps can be classified as very aggressive drivers. Drivers with large accepted gaps were analyzed separately and are presented in the following.

5.2.2.2. Relative Speeds

The drivers that accepted larger gaps were further analyzed using relative speeds of the subject vehicle with the target lane vehicles. To analyze this behavior of drivers, critical gaps were computed for different sets of drivers, categorized based on the range of relative speeds. Relative speed was obtained by subtracting the speed of the target lane vehicle from the speed of the subject vehicle when the subject vehicle accepted the gap. The subject vehicle, the assumed follower, and the assumed leader, increased or decreased the relative speeds to increase the gap between them and facilitate the lane change. The relative speeds ranged from -20 ft/s to 20 ft/s. Drivers were observed to maintain high relative speeds ranging from -10 ft/s to -20 ft/s and 10 ft/s to 20 ft/s while accepting larger gaps. When the relative speeds are higher, the risk of collision is high when accepting a shorter gap. To make a safe lane change, drivers accepted larger gaps.

Figure 5 presents the plot of critical gaps versus the relative speeds. In the plot, x-axis indicates the four ranges of relative speeds, each 10ft/s, and y-axis represents the corresponding critical gaps estimated. Positive relative speeds indicate that the subject vehicle travelled at a speed greater than the corresponding target lane vehicle, and negative relative speeds indicate that the speed of the subject vehicle was less than the speed of the corresponding target lane vehicle. The vehicles with the positive relative speeds (82%) were those with the trailing gap as the governing gap; and most of the drivers with the negative relative speeds (76%) were those with the leading gap as the governing gap. It can be observed that the drivers that maintained higher relative speeds had higher values of critical gaps (1.244 and 1.351 seconds) and those with lower relative speeds had shorter critical gaps (1.005 and 1.056 seconds).

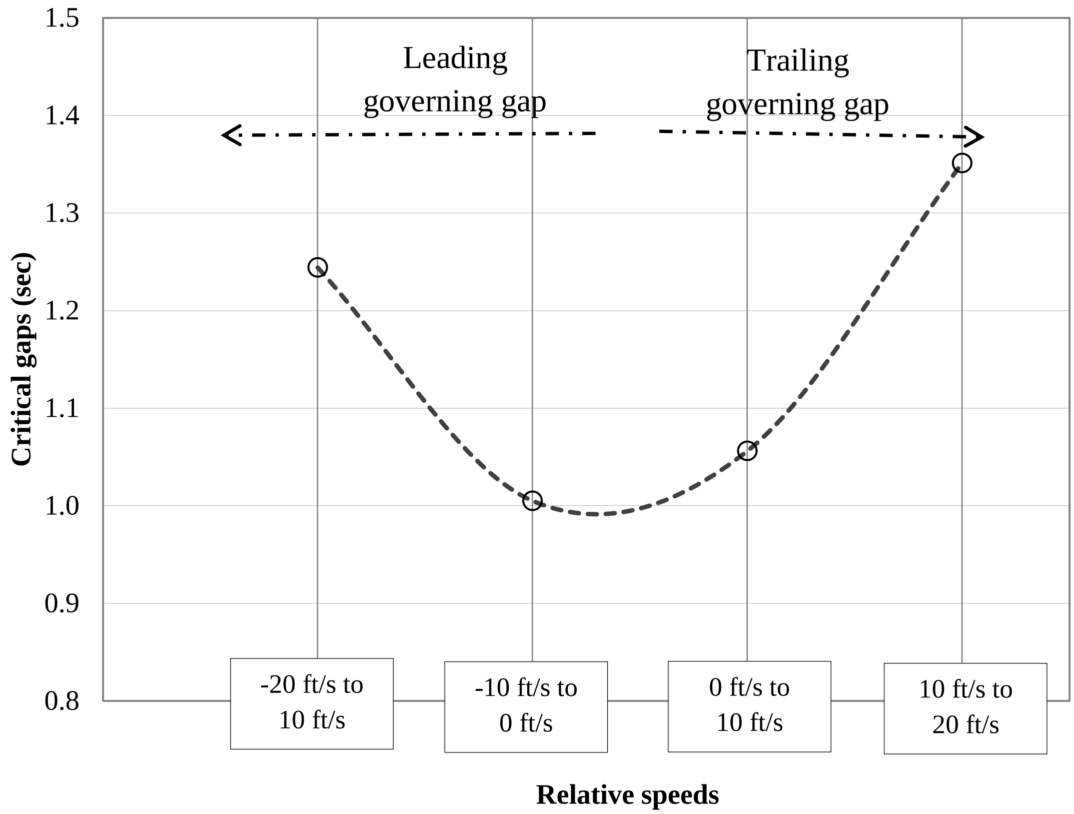


Figure 5 Variation of critical gaps based on relative speeds in congested traffic conditions

Most drivers in maneuvers 1 and 3, with the leading gap as the governing gap, maintained negative relative speeds in the range of -20 to 0 ft/s. The difference in the mean critical gaps in leading governing gap maneuver types (1.040-0.964 = 0.076 second) was smaller when compared to the difference in the mean critical gaps of the corresponding leading governing gap relative speed ranges, -20 to -10 ft/s and -10 to 0 ft/s (1.244-1.005=0.239 second). The difference in the mean critical gaps in the trailing governing gap maneuver types (1.020-0.985 = 0.035 second) was smaller when compared to the difference in the mean critical gaps of the trailing governing gap relative speed ranges, 0 to 10ft/s and 10 to 20ft/s (1.351-1.056=0.295 second).

The difference in the mean values of critical gaps, therefore, was appreciable when the drivers were categorized based on the relative speeds compared to the maneuver types. The number of drivers, however, in the range of -20 to -10 ft/s and 10 to 20 ft/s relative speeds (9 and 8, respectively) were very less compared to -10 to 0 ft/s and 0 to 10 ft/s range of relative speeds (51 and 42, respectively).

5.3. Uncongested Traffic Conditions

5.3.1. Accepted and Rejected Gaps

Table 5 presents the summary statistics of the accepted and rejected gaps for the four maneuvers in uncongested traffic conditions. In the shoulder-to-adjacent movement, the mean of the accepted and LRLA gaps in all maneuvers ranged from 0.801 to 1.320 seconds and 0.718 to 1.263 seconds, respectively with standard deviation varying from 0.505 to 0.979 second and 0.509 to 0.947 second, respectively. In the adjacent-to-shoulder movement, the mean accepted and LRLA gaps in all the maneuvers ranged from 0.591 to 1.259 seconds and 0.533 to 1.193 seconds, respectively with standard deviation varying from 0.389 to 0.790 and 0.374 to 0.784 seconds, respectively.

Maneuvers 1 and 3 from the shoulder lane to the adjacent lane comprised 71% (110 drivers) of the lane changers. In these maneuvers, the subject vehicle interacted closely with the target lane assumed leader and made a lane change. With uncongested traffic conditions being uncongested, most of the target lane vehicles travelled at the posted speed limit. The lane changers from the on-ramp did not move past the target lane vehicles and as a result of uncongested conditions gaps were available, therefore decelerated and made a lane change. The lane changers in the shoulder lane maintained speeds less than the target lane assumed leaders and made a lane change behind the leaders. This behavior was not observed in the lane changes from the adjacent lane to the shoulder lane, the number of drivers in all the maneuvers in this movement were almost the same. Drivers equally preferred the four maneuvers in moving to the off-ramp from the highway.

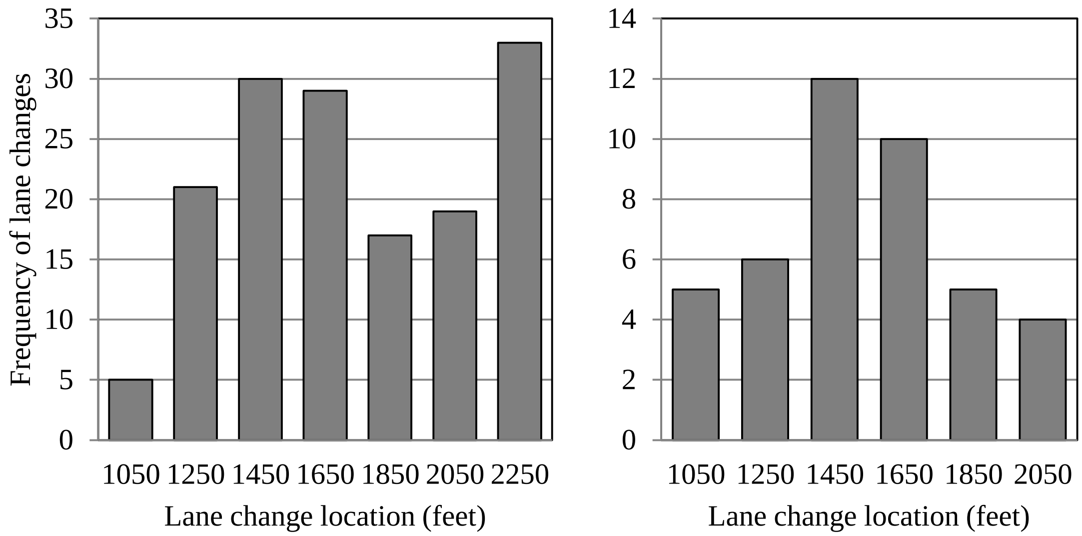
TABLE 5 Summary Statistics for Accepted, LRLA Gaps and Critical Gaps based on Maneuver Type in Uncongested Traffic Conditions

Shoulder lane to Adjacent lane movement								
Maneuver type	**1**		**2**		**3**		**4**	
Governing gap	**Leading**		**Trailing**		**Leading**		**Trailing**	
Gap type	**Accepted**	**LRLA**	**Accepted**	**LRLA**	**Accepted**	**LRLA**	**Accepted**	**LRLA**
No. of Lane Changes	60	60	15	15	50	50	29	29
Mean	0.801	0.718	0.806	0.728	1.320	1.263	1.177	1.129
Median	0.582	0.503	0.723	0.686	1.204	1.058	0.896	0.859
St. Dev.	0.713	0.711	0.505	0.509	0.813	0.785	0.979	0.947
Maximum	4.101	4.095	1.772	1.688	3.309	3.172	4.956	4.724
Minimum	0.212	0.159	0.230	0.177	0.281	0.249	0.328	0.288
Lognormal MLE's								
Mean	0.852	0.804	0.874	0.828	1.077	1.055	1.012	0.992
St. Dev.	0.243	0.240	0.245	0.256	0.326	0.325	0.288	0.289
Critical gap								
Mean	0.827		0.849		1.065		1.000	
St. Dev.	0.239		0.240		0.322		0.283	
Adjacent lane to Shoulder lane movement								
Maneuver type	**1**		**2**		**3**		**4**	
Governing gap	**Leading**		**Trailing**		**Leading**		**Trailing**	
Gap type	**Accepted**	**LRLA**	**Accepted**	**LRLA**	**Accepted**	**LRLA**	**Accepted**	**LRLA**
No. of Lane Changes	11	11	11	11	9	9	11	11
Mean	0.697	0.591	0.591	0.533	1.259	1.193	0.891	0.826
Median	0.562	0.479	0.498	0.425	1.096	0.984	0.757	0.716
St. Dev.	0.389	0.374	0.436	0.428	0.790	0.784	0.653	0.588
Maximum	1.707	1.574	1.833	1.732	2.517	2.436	2.198	1.882
Minimum	0.278	0.205	0.286	0.201	0.304	0.255	0.238	0.234
Lognormal MLE's								
Mean	0.832	0.769	0.764	0.723	1.060	1.031	0.901	0.873
St. Dev.	0.174	0.182	0.179	0.194	0.348	0.361	0.304	0.288
Critical gap								
Mean	0.799		0.742		1.040		0.874	
St. Dev.	0.168		0.176		0.330		0.250	

For maneuvers 1 and 2, shoulder-to-adjacent movement, drivers either accelerated or decelerated to pass the target lane vehicle and made a lane change. This behavior can be stated as attentive behavior to make a lane change. Most of these drivers, as a result, accepted shorter gaps (0.801 and 0.806 seconds) compared to drivers in maneuvers 3 and 4 (1.320 and 1.177 seconds). In maneuvers 3 and 4, the drivers were timid. These drivers did not move past the target lane vehicle. They maneuvered between the assumed leader and assumed follower to make a lane change. In these maneuvers, the drivers accepted slightly larger gaps when compared to maneuvers 1 and 2. Further, the standard deviation of the accepted gaps in maneuvers 3 and 4 (0.813 and 0.979 second, respectively) was larger than the standard deviation of the accepted gaps in maneuvers 1 and 2 (0.713 and 0.505 second, respectively). This difference indicates that drivers for maneuvers 3 and 4 the variation in accepted gaps was high. This behavior was observed in adjacent-to-shoulder movement as well.

Further, the lane changers were found to utilize the shoulder lane of the weaving section to accelerate or decelerate to reach the speed limit of the respective target lane. Higher frequency of lane changes near the off-ramp in case of shoulder-to-adjacent movement (represented in Figure 6(a)(i)) indicated that the lane changers in the shoulder lane accelerated from the off-ramp and made a lane change. The frequency of lane changes, therefore, observed at the end of the shoulder lane was high for shoulder-to-adjacent movement. On the other hand, most of the adjacent-to-shoulder lane drivers made a lane change by the middle of the weaving section (1500 to1700 feet, represented in Figure 6(a)(ii)) and slowed down sufficiently in the shoulder lane before moving on to the off-ramp as the speed limits ramp was lower.

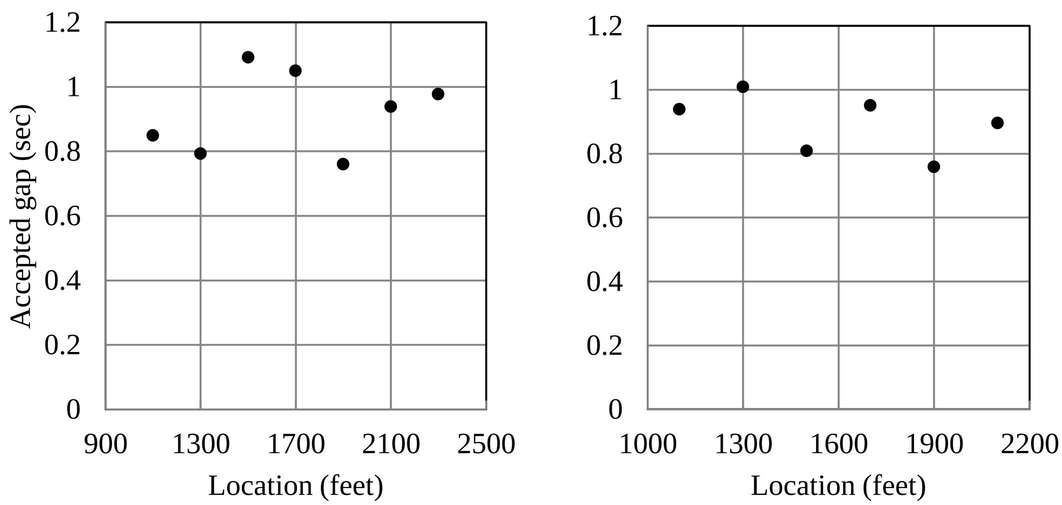
The accepted gaps did not vary much along the weaving section. Figure 6(b) represents the variation of the accepted gaps along the weaving section. It can be observed that the accepted gaps did not vary over the length of the weaving section for uncongested traffic conditions. Hence, drivers were able to find an acceptable gap to make a lane change. Drivers, therefore, accepted similar sized gaps along the weaving section. Drivers, in fact, focused on adjusting their speeds to the prevailing target lane speeds while traveling through the weaving section.



(i) Shoulder to Adjacent movement

(ii) Adjacent to Shoulder movement

(a) Variation of frequency of lane changes along the weaving section based on type of movement



(i) Shoulder to Adjacent movement

(ii) Adjacent to Shoulder movement

(b) Variation of accepted gap along the length of the weaving section

Figure 6 Relationship between the merge location, frequency of lane changes and accepted gaps based on the type of movement in uncongested traffic conditions

5.3.2. Critical Gaps

Critical gaps were estimated using accepted gaps and LRLA gaps. Both the accepted gaps and LRLA gaps followed lognormal distribution. Critical gaps, therefore, were assumed to follow a lognormal distribution. Table 5 presents the critical gap values estimated for all the maneuvers in uncongested traffic conditions. Further, the effect of relative speeds on the critical gaps was also examined and the analysis of the results is presented in this section after the maneuver types.

5.3.2.1. Maneuver Types

The mean of the critical gaps, in all the maneuvers in shoulder-to-adjacent movement, ranged from 0.827 to 1.065 seconds with a standard deviation of 0.239 to 0.322 second. The mean of the critical gaps, in all the maneuvers in adjacent-to-shoulder movement ranged from 0.742 to 1.084 seconds with a standard deviation of 0.168 to 0.390 second. Consistent driver behavior was observed as the estimated mean critical gap values fall in between the MLEs of accepted and LRLA gaps.

Mean of the critical gaps in maneuvers 1 and 2 (0.827 and 0.849 seconds, respectively) were shorter when compared to maneuvers 3 and 4 (1.065 and 1.000 seconds, respectively) in shoulder-to-adjacent movement. This shorter mean critical gap meant that the drivers were aggressive in those maneuvers. Further, the standard deviation of the mean of the critical gaps was shorter for maneuvers 1 and 2 when compared to maneuvers 3 and 4 which meant that there were good numbers of drivers who rejected and accepted shorter gaps. It can be, therefore, stated that the aggressive drivers performed maneuvers 1 and 2 whereas timid drivers preferred the maneuvers 3 and 4.

A difference of 0.238 second was observed in the mean values of critical gaps in maneuvers 1 and 3 for which the leading gap was the governing gap, and a difference of 0.152 second in the mean values of critical gaps in maneuvers 2 and 4 when the trailing gap was the governing gap. Further, there were only slight differences between the leading and trailing gaps were observed.

5.3.2.2. Relative Speeds

Drivers were further categorized based on the relative speeds to examine the effect of relative speeds on the gap acceptance behavior similar to the observation in the congested traffic conditions. Most of the positive relative speeds were in the case of assumed followers and most of the negative speeds were in the case of assumed leaders.

In uncongested traffic conditions, subject vehicle drivers maintained relative speeds in the range of -30 ft/s to 20 ft/s with the target lane vehicles. The range of relative speeds was higher with the target lane assumed leaders compared to the assumed followers. Eighty seven percent of the drivers were observed to maintain a range of relative speeds between -20 to 10 ft/s. Few drivers (10) in the target lane travelled at high speeds and, as a result, the relative speed of the subject vehicle with those vehicles was in the range of -20 to -30 ft/s. These vehicles were observed to be the assumed leaders and were traveling at a speed, higher than the posted speed limit. The subject vehicle, therefore, maintained a lower speed and made a lane change behind them. Even though the relative speeds were high, the vehicles were within the interacting distance and the subject vehicle interacted closely with the assumed leader than the assumed follower. There were few drivers (16), On the other hand, that travelled at lower speeds compared to the speed limit and when the subject vehicle drivers accelerated, the relative speeds, as a result, with those vehicles were in the range of 10 to 20 ft/s.

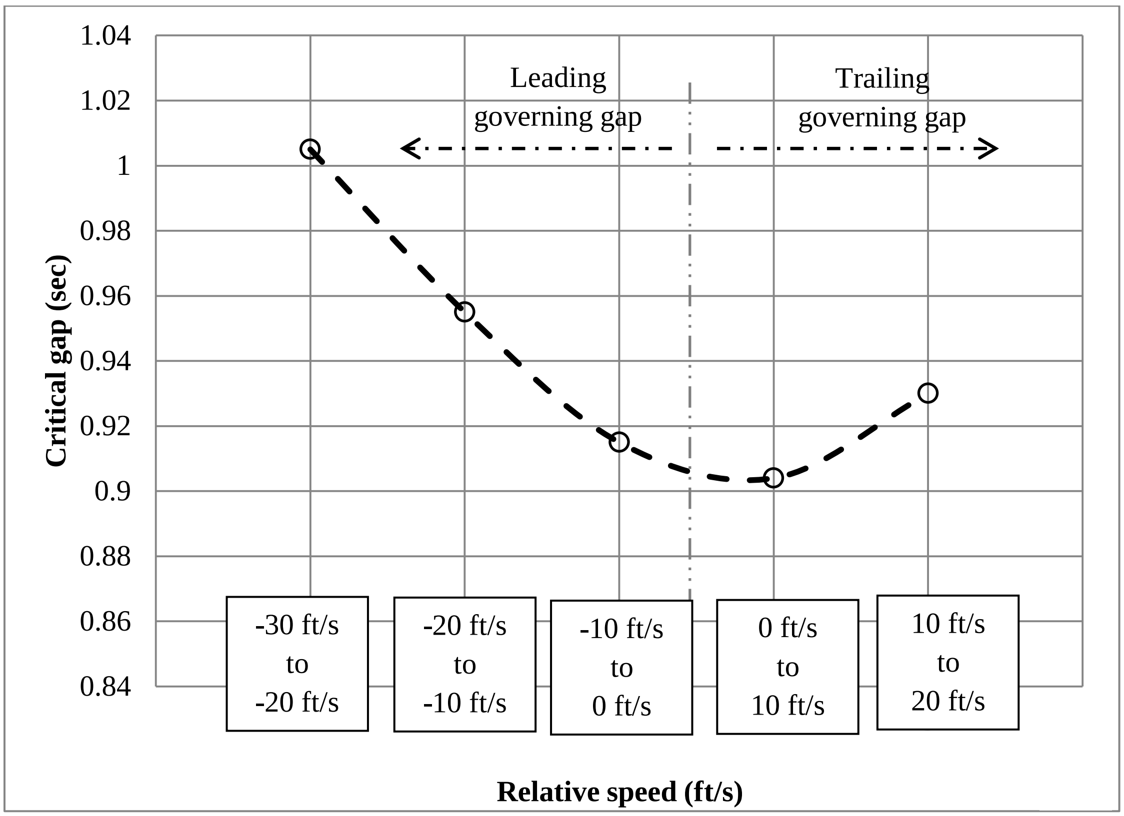


Figure 7 Variation of critical gaps based on relative speeds in uncongested traffic conditions

Figure 7 presents the variation of the critical gaps with relative speeds in uncongested traffic conditions. The critical gaps reduced from 1.005 to 0.915 second for a range of relative speeds from -30 to 0 ft/s and from 0.904 to 0.93 second for 0 to 20 ft/s.

A difference of 0.15 second in mean critical gaps for a difference of 50 ft/s in relative speeds was observed. The critical gap was not affected as much by the relative speeds in uncongested traffic conditions compared to the congested traffic conditions.

6. DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

NGSIM data collected on I-80 were utilized in this paper to analyze the gap acceptance and rejection behavior of drivers during a lane change in both the congested and uncongested traffic conditions. To analyze the interaction of the subject vehicle with both the assumed leader and the assumed follower, the complete process of a lane change was observed. Drivers, during a lane change, were found to interact closely with the assumed leader and the assumed follower. The gap between the subject vehicle and one of the closely interacting target lane vehicles was observed to govern the lane change and is termed as the governing gap in this paper. The governing gap dictates the lane change and drivers wait till the governing gap, an acceptable gap is greater than the critical gap. This governing gap was observed in both congested and uncongested traffic conditions. Drivers behaved consistently using the governing gap, and inconsistently with the other gap i.e., the non-governing gap. Identifying the governing gap during a lane change also indicates consistent driver behavior. As a result, drivers in the data set are retained (not termed as inconsistent and discarded), thus providing a fuller set of data. The results, thus obtained, represent the realistic driver lane change behavior.

Critical gaps were computed using the largest rejected less than the accepted (LRLA) gap. Accepted, LRLA and critical gaps followed the lognormal distribution in both congested and uncongested traffic conditions. Lognormal distribution is, therefore, proposed to be used in lane change algorithms in microscopic traffic simulation models for generating critical gaps.

Four types of lane change maneuvers were identified in both the congested and uncongested traffic conditions. In congested conditions, about 70% of the drivers in the data showed attentive behavior in their maneuvers to make a lane change and these drivers were observed to accept governing gaps in the range of 0.5 to 1.7 seconds. This range of accepted governing gaps resulted due to the congested traffic conditions and as both the vehicles, the assumed leader and assumed follower, were interacting with the lane changer. In uncongested traffic conditions, about 70% of the drivers, in the shoulder-to-adjacent movement, interacted closely with the assumed leader and made a lane change by maintaining a lower speed with the assumed leader.

In congested traffic conditions, although drivers maneuvered in different ways to make a lane change, the critical gaps were not significantly different for different maneuvers whereas in uncongested traffic conditions, critical gaps varied with maneuver type. Drivers in maneuvers 3 and 4 had larger critical gap when compared to maneuvers 1 and 2. Aggressive driver behavior was observed for maneuvers 1 and 2 whereas timid or relaxed driver behavior was observed for maneuvers 3 and 4. Therefore, it can be stated that drivers accepted different sized gaps based on the type of maneuver and type of governing gap. This behavior, however, was not observed in congested traffic conditions.

To better understand the driver behavior, drivers were categorized based on relative speeds as well. In congested traffic conditions, about 85% of the drivers maintained relative speeds between -10 ft/s to 10 ft/s and accepted gaps less than 1.5

seconds. A small percentage of drivers, however, maintained higher relative speeds ranging from -20 ft/s to -10 ft/s and 10 ft/s to 20 ft/s. Drivers, as a result, accepted larger gaps in order to minimize the risk of collision. The mean critical gaps varied with the variation in relative speeds. This relation, however, was not observed in case of uncongested traffic conditions.

The range of the relative speeds was higher when compared to the speeds of the individual vehicles in congested data whereas in uncongested data, the relative speeds were not very high when compared to the speeds of the individual vehicles. The average speed in congested conditions was about 25 ft/s whereas average speed in uncongested conditions was about 70 ft/s. These relative speeds, therefore, were about one-third of the individual vehicles' speeds in uncongested traffic conditions whereas the relative speeds were almost double the speed of the individual vehicles' speeds in congested traffic conditions. The critical gaps, as a result, in uncongested traffic conditions did not vary appreciably with the relative speeds as they varied in congested traffic conditions.

For a simple lane change model (*27*), three parameters: governing gap, type of maneuver and a critical gap distribution with a mean value of based on the empirical data are sufficient to model driver lane change behavior. For a sophisticated lane change model, in addition to these three parameters, critical gaps based on the relative speeds will help in better representation of realistic driver lane change behavior in congested traffic conditions. In uncongested traffic conditions, critical gap distributions based on the governing gap and maneuver type will be sufficient to represent the realistic driver lane change behavior.

Further study is recommended to estimate the critical gaps for different types of facilities. Studies to comprehend driver behavior in discretionary and multiple lane changes can also be conducted. The effect of the governing gap can also be explored for different types of facilities.

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