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Lane Change Rates at Freeway Weaving Sites: Trends in HCM6 and from NGSIM Trajectories

Ishtiak Ahmed[1], Dezhong Xu[1], Nagui Rouphail[1], and Alan Karr[2]

Abstract

Concerns have been raised about the HCM6 weaving method's lack of sensitivity to weaving segment length. This study explores the trends in HCM6 as they relate to lane change estimates and their impact on the segment speed and level of service (LOS). The study also compares HCM6 estimates of lane changes against empirical data from an NGSIM weaving site. Thus, the objectives of this study are twofold: (*a*) critically investigate the effect of weaving length on lane change and associated speed model estimates in HCM6, and (*b*) analyze trends in lane changes against congestion levels using detailed NGSIM trajectory data, comparing against HCM6 estimates. For (*a*) it was found that the lack of sensitivity to weave length is because of the absence of this parameter in the nonweaving lane change and speed models. For (*b*), a comparison of HCM6 lane change rates with NGSIM, US-101 data confirmed that the HCM6 estimates for weaving vehicles are fully consistent with those at the NGSIM site, controlling for density. In contrast, nonweaving lane change estimates in HCM6 did not deliver the expected trends, with more discretionary lane changes predicted as congestion increased. Finally, analysis of lane change patterns at the NGSIM site revealed a tendency for early merging for freeway to ramp traffic and uniform merging for ramp to freeway traffic over the length of the weave. Interestingly, a speed analysis showed that in most cases, a higher frequency of discretionary lane changes yielded lower travel times for drivers executing them.

The operational analysis of weaving segments in the Highway Capacity Manual, HCM6 edition (*1*) is predicated on a robust estimation of lane change frequencies for both weaving and nonweaving vehicles. There has been some concern about the results of the HCM6 methodology because it apparently lacks sensitivity to the weaving segment length, implying that performance measures such as speed or density will not materially affect the level of service (LOS) as the weaving segment length increases. There is also the opportunity to verify and compare those lane change frequencies with empirical data from existing full-trajectory data sources such as the NGSIM data sets generated at weaving segments (*2*). In the process of making those comparisons, the paper proposes intuitive lane-based and vehicle-based performance measures at weaving segments to aid in the understanding of those effects. This paper presents a critical analysis of the existing HCM6 method, identifies possible paths for improving its lane change and speed models, and compares them to observed lane changes at an NGSIM weaving site. The motivation for those lane changes is also explored. Although the work presented in this paper does not propose a revised HCM methodology, it points to areas in the existing procedure in which model adjustments should be considered and prioritized. In summary, the objectives of this study are twofold: (*a*) critically investigate the effect of weaving length on lane change and associated speed model estimates in HCM6; and (*b*) analyze trends in lane changes against congestion levels using detailed NGSIM trajectory data, comparing against HCM6 estimates.

This paper is organized as follows. Following the introductory section, a literature review of lane change models and the use of NGSIM data is provided. The methodology is then discussed, by first providing a detailed, critical analysis of the current HCM6 lane change models and how they are extended to predict lane change rates. Next, trajectory data preparation from the NGSIM site is described to enable an HCM-type

[1]Department of Civil, Construction, and Environmental Engineering, North Carolina State University, Raleigh, NC
[2]RTI International, Research Triangle Park, NC

Corresponding Author:
Address correspondence to Ishtiak Ahmed: iahmed2@ncsu.edu

weaving analysis. The results section compares HCM6 lane change estimates against observations from the NGSIM dataset. Next, a lane-based, lane change rate analysis of the NGSIM trajectories is conducted to identify the extent, direction, and motivation of discretionary lane changes. Finally, a summary of the findings and directions for future research are discussed.

Literature Review

The review of literature relevant to this study is presented in two parts. The first part reviews past studies on weaving segment analyses. The second part discusses the applications of NGSIM data and its quality in relation to analyzing lane changing behavior during congested conditions.

Weaving Segment Analysis

Several studies have investigated the relationship between weaving segment capacity and operating speed with different macroscopic parameters (*3*, *4*). The relationship between speed and ramp spacing of a weaving segment was investigated by (*3*) using video record data from seven weaving segments in Texas using a linear regression model, and it was shown that the operating speed of the weaving segment could be modeled as a function of the total exiting volume, the ratio of the ramp to ramp volume to the total entry volume, and the segment length. The coefficient for segment length in the model revealed that a 10-mph increment in operational speed could be achieved by increasing the base-weaving length by 4,000 ft. However, the same investigation conducted in a VISSIM simulation revealed that the operational speed is sensitive to the segment length only up to 2,000 ft, which conflicted with the findings from the regression model. The models developed by Roess & Ulerio (*4*) for predicting capacity and speed of a weaving segment were based on short period traffic data but for a variety of road characteristics. The models were included in the 2010 HCM and retained in HCM6. Details of these models are discussed later.

Trajectory data obtained from airborne videos were used by (*5*) and (*6*) to analyze the position of mandatory lane changes and the resulting turbulence in a weaving segment. The data collected by (*5*) was confined to a single weaving site, which showed that all mandatory lane changes by the weaving vehicles were completed within the first 60% of the total length of the segment. The data used by (*6*) came from eight weaving sites, but the findings were similar to that obtained by (*5*). It was found that about 65% to 95% of the weaving lane changes occurred within the first 25% of the total length. Based on these findings, these studies inferred that the low sensitivity of speed to weaving segment length could be attributed to the under-usage of the segment length for changing lanes.

Applications of NGSIM Data and Its Quality

Since NGSIM datasets for three freeway sites have become available (*2*), many researchers have used them for analyzing various microscopic traffic patterns, such as freeway lane change dynamics and car-following behavior. Application of NGSIM data (US-101, I-80, and I-395) for analyzing lane change dynamics is significant in number because all the freeway sites contain multiple ramps. Most studies have focused on analyzing the lane changes microscopically in relation to duration, speed, acceleration and deceleration patterns, and key exogenous variables that might affect the lane change intent decisions (*7–9*).

The duration and speed of vehicles when changing lanes were found to be significantly different between heavy vehicles and passenger cars at the US-101 and I-80 sites (*8*). In addition, variations in acceleration and deceleration rates while changing lanes, along with the longitudinal speed were characterized using the fifth General Motors (GM) model in this study. Another study adopted a mesoscopic approach to model discretionary lane changes by dividing the US-101 site into several cells. The likelihood of conducting discretionary lane changes was estimated using a logistic regression model, in which the speed and density difference between the origin and target lane were found as the most influential factors behind discretionary lane changes. The use of the I-395 site data was found only in one study (*7*). It uses an artificial neural network (ANN) and multiple linear regression (MLR) to model the lane changes a few seconds before their execution. The independent variables included subject vehicle speed and acceleration, and distance and speed of the leading and following vehicles in the subject and the target lane relative to the subject vehicle.

Although several studies raised some concern about the quality of the NGSIM data (*9–11*), the reported errors were considered to mostly affect the derived microscopic parameters such as individual vehicle speed and acceleration. Some studies used simple smoothing algorithms before working with the data (*7*, *8*). However, most studies used the discrete lane positions as reported in the NGSIM database. One study that characterized the lane change duration from US-101 reported that the lane positions were sometimes inconsistent with the raw video by only a few time steps (*9*). Some anomalies in the lane position were attributed to aborted lane changes and changing two lanes in quick succession.

From the above review, the following observations are deemed noteworthy:

- Findings from different studies about the sensitivity of the speed and capacity of a weaving segment to the segment length and lane change rate vary significantly. Therefore, the guidance currently in practice needs further investigation.
- The lane changes in a weaving segment are classified by their origin–destination (O-D) route. To the authors' knowledge, there is a gap in research for lane-based lane change analysis of mandatory and discretionary lane changes.

Methodology

The study first provides a critical analysis of the HCM6 method, focusing on the lane change models and sensitivity of the method to weave length. It then proposes additional lane change measures at the vehicle level that can provide insights into the HCM method lane change patterns as well as enabling comparisons with empirical data sources. Finally, it explains how the NGSIM data are prepared for an HCM weaving type analysis.

Critical Analysis of HCM6 Weaving Method

The incorporation of weaving segment length into the current HCM method occurs in several models. First is the density-based capacity estimate, in which the weaving segment capacity is found to be proportional to the short segment length (L_s), as in

$$C_{\mathrm{iwl}} = C_{\mathrm{ifl}} - \left[438.2(1 + \mathrm{VR})^{1.6}\right] + [0.0765L_s] + [119.8N_{\mathrm{wl}}] \tag{1}$$

where

C_{iwl} = capacity of the weaving segment under equivalent ideal conditions, per lane (pcphpl),

C_{ifl} = capacity of a basic freeway segment with the same free flow speed (FFS) as the weaving segment under equivalent ideal conditions, per lane (pcphpl);

L_s = weaving segment short length which is the distance in feet between the endpoints of any barrier markings (solid white lines) in a weaving segment that discourage lane changing; and

N_{wl} = number of weaving lanes.

The relationship above implies that higher capacities are achieved when weaving volumes are low, the short length is increased, or when weaving maneuvers do not require an extensive, minimum number of lane changes. The next set of models that use the short length is for the estimation of the lane change frequencies for both weaving and nonweaving traffic, with the caveat that under certain conditions the length is not incorporated in the prediction. Thus, for weaving traffic, the expected number of lane changes is estimated as

$$\mathrm{LC}_w = \mathrm{LC}_{\min} + 0.39[(L_s - 300)^{0.5}N^2(1 + \mathrm{ID})^{0.8}] \tag{2}$$

where

LC_w = equivalent hourly rate at which weaving vehicles make lane changes within the weaving segment (lc/h);

$\mathrm{LC}_{\min}$ = minimum equivalent hourly rate at which weaving vehicles must make lane changes within the weaving segment to complete all weaving maneuvers successfully (lc/h);

N = number of lanes within the weaving segment (ln); and

ID = interchange density (interchanges per mile).

The above model shows that the frequency of weaving traffic lane changes includes the mandatory lane changes to execute the weaving maneuver ($\mathrm{LC}_{\min}$) in addition to discretionary lane changes. The second term includes only segment and section geometric variables, namely the square of the adjusted short length, the number of lanes in the segment, and the interchange density. Interestingly, no effects of demand volumes or congestion levels are included in this estimate. For nonweaving vehicles, all lane changes are of course discretionary. Depending on the value of a nonweaving index (I_{nw}), in most cases, the following lane changing model for nonweaving vehicles applies:

$$\mathrm{LC}_{\mathrm{nw1}} = (0.206v_{\mathrm{nw}}) + (0.542L_s) - (192.6N) \tag{3}$$

where v_{nw} is the demand flow rate for nonweaving vehicles (pcph).

Similar to the weaving lane change model, the nonweaving vehicles' lane changes increase as the short length increases. This is important to note because the total number of lane changes ($\mathrm{LC}_{\mathrm{all}}$) will increase as the weaving length increases, assuming all other variables are kept fixed. On the other hand, it is unclear why weaving traffic lane changes tend to increase with the square of the number of lanes, whereas at the same time the nonweaving lane changes will tend to decrease as the number of lanes increases. The weaving traffic speed (S_w) model uses the total number of lane changes per unit short length of the weave, based on

$$S_w = 15 + \left(\frac{\mathrm{FFS} \times \mathrm{SAF} - 15}{1 + W}\right);\ \text{where } W = 0.226\left(\frac{\mathrm{LC}_{\mathrm{all}}}{L_s}\right)^{0.789} \tag{4}$$

where FFS is the free flow speed, and SAF is the speed adjustment factor.

Table 1. Sensitivity of Speed, Density, and LOS to Weaving Segment Length in HCM6

Length L_s (ft)	Total lane changes LC_{all}	S_w (mph)	S_{nw} (mph)	S (mph)	Density (pcpmpl)	LOS
500	3,008	38.3	36.6	37.24	29.00	D
750	3,312	41.0	36.6	38.20	28.27	D
1,000	3,625	42.7	36.6	38.76	27.86	C
1,250	3,908	43.9	36.6	39.14	27.59	C
1,500	4,172	44.9	36.6	39.44	27.38	C
1,750	4,424	45.6	36.6	39.65	27.24	C
2,000	4,666	46.2	36.6	39.83	27.12	C

Nonweaving traffic speed, on the other hand, is not dependent on weaving length, but strictly on overall volume per lane and the minimum number of lane changes:

$$S_{\text{nw}} = \text{FFS} \times \text{SAF} - (0.0072\text{LC}_{\text{min}}) - \left(0.0048\frac{v}{N}\right) \quad (5)$$

A closer examination of the lane change and speed equations reveals a possible contributor to the lack of sensitivity of quality of service to weaving segment length. First, the frequency of lane changes tends to increase with the weaving segment length, which is sensible. When calculating the weaving vehicle speed, it can be shown that the parameter W, which represents the weaving impedance correctly drops as the length increases, yielding predictably higher weaving speeds as the length increases. On the other hand, the nonweaving traffic speed (which typically applies to 60% to 80% of all vehicles in the weave) has zero sensitivity to changes in the weaving segment length. With the predominant traffic essentially nonweaving, any increase in the weaving segment length will have a minimal effect on overall speed and thus on overall density and LOS.

A simple numerical exercise helps to illustrate this predicament. Here, it is assumed that an overall demand (v) of 6,480 pcph, 60 mph FFS, six-lane urban ramp weave with volume ratio (VR) = 0.39 (on the high end of weaving intensity). Interchanges are assumed to occur at 1/2-mi intervals. The exercise consists of varying the short length in increments of 250 ft and generating the resulting density and LOS. Table 1 shows the results for a weaving length ranging from 500 to 2,000 ft.

This example vividly demonstrates the lack of sensitivity of the procedure's service measures to weaving segment length. By quadrupling length from 500 to 2,000 ft, density decreased by only 1.82 pcpmpl (or ~6.3%). Had the VR been lower, that difference would shrink even more. It is also clear that any improvement to the method estimates should focus on improving the nonweaving speed model. Presumably, nonweaving vehicles should also benefit from extending the weaving length by spacing the lane changes across a longer distance. One potential approach is to recalibrate the two speed models, using the same model form as the weaving speed model in Equation 4, applying the relevant lane changes appropriate for each. Further comparisons of HCM6 lane changes against field data are provided later in this paper.

Additional Lane- and Vehicle-Based Performance Measures

Basic lane change statistics in HCM6 include the total number of lane changes for weaving, nonweaving, and all vehicles. Although those measures are useful, the use of lane change measures on a per vehicle basis produces better insights into the lane change patterns, more so than the aggregate statistics. They also are more suitable for use with high-resolution vehicle trajectory data for which lane position is known or can be estimated for each vehicle from lat-long positions. Finally, the per vehicle lane change estimates are more appropriate for the purpose of distinguishing between mandatory and discretionary lane changes, and for those occurring from individual lanes when such data are available.

To begin with, three classes of lane change types in weaving segments are defined. Those are predicated on knowing either the vehicle entry and exit lane, or more broadly the origin and destination (freeway or ramp) observed for each vehicle within the weaving section. HCM6 provides information only at the O-D level, not at the lane level. The three classes are (*a*) the minimum number of lane changes per vehicle assuming proper prepositioning, (*b*) the required number of lane changes based on entry and exit lanes, and (*c*) the actual number of observed lane changes. It is useful to illustrate those concepts with the aid of an example, as shown in Figure 1. Here the lanes are numbered from the shoulder (Lane 1) to the median (Lane 5).

In this illustration, the vehicle in Lane 5 is tracked and it transpires that:

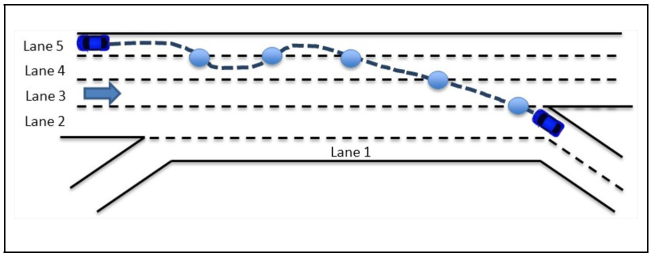

Figure 1. Illustrative example of lane change rate measures.

(a) The minimum number of lane changes is zero because had that vehicle in Lane 5 been correctly pre-positioned in Lane 2 to exit, it would not need to execute any lane changes;
(b) The required number of lane changes to exit, assuming entry in Lane 5, is three; and
(c) The actual number of lane changes is five, as shown in the figure.

This process can be applied to vehicles entering in each lane, and exiting in any lane. The minimum number of lane changes is strictly a function of the segment configuration, whereas the required number is dependent on the entry and exit lanes, a driver choice. The difference between actual and required lane changes can also be interpreted in terms related to the driver level of aggressiveness. In relation to aggregate weaving and nonweaving vehicles in this example, only traffic weaving from the on-ramp to the freeway must execute a minimum of two lane changes. All other lane changes would be considered discretionary. Thus, the "per vehicle" minimum number of mandatory lane changes, or lane change rate in the example above is calculated as

$$\mathrm{LCV}_w^{\min} = \frac{2 \times v_{rf}}{v_w} \quad (6)$$

So that if ramp weaving vehicles constituted 30% of all weaves, $\mathrm{LCV}_w^{\min} = 0.60$.By contrast, for a ramp weave segment with a single auxiliary lane, $\mathrm{LCV}_w^{\min} = 1$, where LCV_w is the lane change per weaving vehicle. For nonweaving vehicles, $\mathrm{LCV}_{\mathrm{nw}}^{\min}$ is by definition zero. Other vehicle-based lane change rates are defined in Equations 7 to 11 below, where the superscript (*d*) refers to discretionary lane changes and VR is the volume ratio:

$$\mathrm{LCV}_w = \frac{\mathrm{LC}_w}{v_w} \quad (7)$$

$$\mathrm{LCV}_{\mathrm{nw}}^d = \frac{\mathrm{LC}_{\mathrm{nw}}}{v_{\mathrm{nw}}} \quad (8)$$

$$\mathrm{LCV}_w^d = \mathrm{LCV}_w - \mathrm{LCV}_w^{\min} \quad (9)$$

$$\mathrm{LCV}^d = \mathrm{LCV}_w^d + \mathrm{LCV}_{\mathrm{nw}}^d \quad (10)$$

$$\mathrm{LCV}_{\mathrm{all}} = \mathrm{VR} \times \mathrm{LCV}_w + (1 - \mathrm{VR}) \times \mathrm{LCV}_{\mathrm{nw}} \quad (11)$$

The application of these measures will be demonstrated using the high-resolution NGSIM dataset on US-101 described in the next section. Those will be contrasted with the lane change rate estimates in the HCM6 procedure.

NGSIM Data Preparation

The dataset used here is from US-101, or Hollywood Freeway in Los Angeles, California (*2*). A second nearby site on I-80 was also considered but later discarded because of its unusual auxiliary lane geometry, making it operate as an on-off-ramp junction. US-101 is a ramp weave segment with five mainline lanes and a single auxiliary lane, as shown in Figure 2. The weave length gore-to-gore is 698 ft with trajectory data collected at 10 Hz intervals over a longer distance of 2,100 ft. The original data were extracted from high-resolution videos, then subsequently processed through a video image processor (NG Video) and manually verified and corrected for any discrepancies. Data were collected on June 15, 2005 for three 15-min time periods from 7:50 to 8:35 a.m. Individual lanes were numbered from 1 (leftmost lane) to

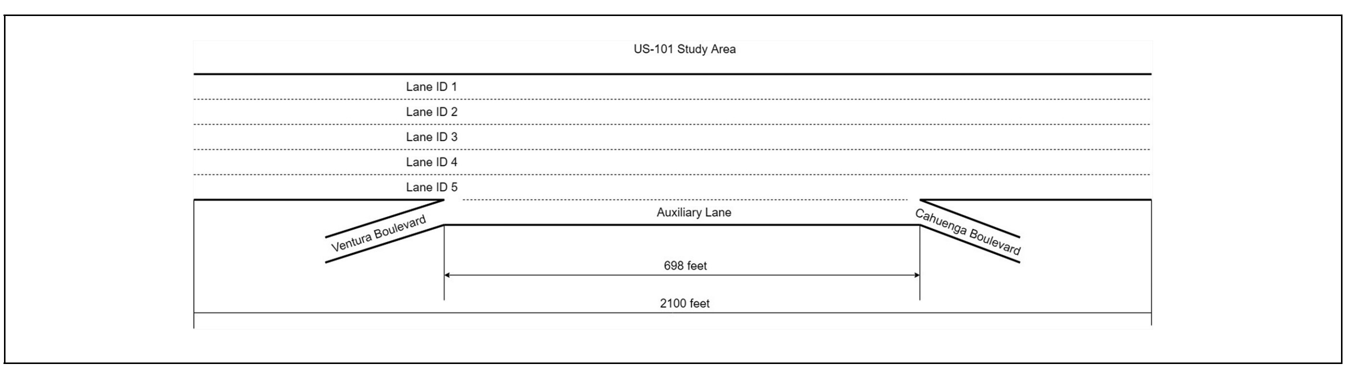

Figure 2. Schematic of the US-101 weaving segment.

6 (auxiliary) with traffic entering at Ventura Boulevard assigned to Lane 7, and that exiting at Cahuenga Boulevard assigned to Lane 8. Each trajectory observation included the lane number the vehicle was present at, and therefore the analyst can track the frequency and position of all lane changes both mandatory and discretionary for both weaving and nonweaving traffic.

The dataset contained records for 4,824 vehicles, of which 4,681 vehicles were passenger cars, 105 were heavy vehicles, and 38 were motorcycles. Because lane changing patterns for motorcycles proved to be quite excessive, possibly biasing the results, those vehicles were excluded from the analysis.

The next step was to extract and summarize the information related to lane changes. Because the dataset contained lane ID information at 10 Hz resolution, by recording the entering, current, and exiting lane ID for each vehicle, the number, direction, and origin and destination of each vehicle were documented. This process enabled us to aggregate the data at the weaving and nonweaving traffic levels, as well as being able to observe all mandatory and discretionary lane changes within the weaving segment. In essence, all the lane change rate measures described in the previous section can be extracted for this site.

In relation to the effect of weaving segment length on operations described earlier, each weaving vehicle's first and last point of contact in the auxiliary lane was tracked. The intent was to ascertain whether those maneuvers were uniform over the length of the auxiliary lane, or simply concentrated near the on- and off-ramp gore areas. Finally, an interesting hypothesis that can be gleaned from the data is whether lane changes are in fact beneficial—from a mobility perspective—to drivers who execute them. The large sample of lane changes allowed us to extract the space mean speed (SMS) for each vehicle traversing the segment based on the number of lane changes the driver executes. This was done by summing the 10-Hz speed observations across the weaving segment and dividing by the travel time for each vehicle. Space mean speed distributions categorized by the number of lane changes were constructed and are presented in the results section.

Results

Observed Trends in Lane Change Rates

On extracting weaving and nonweaving traffic lane changes from the US-101 trajectories, those were compared with the HCM6 procedure estimates on the basis of the value of overall segment density. This approach was necessary because the NGSIM site operates in the congested flow regime (low flows and speeds), and the HCM6 procedure is invalid when the demand to capacity

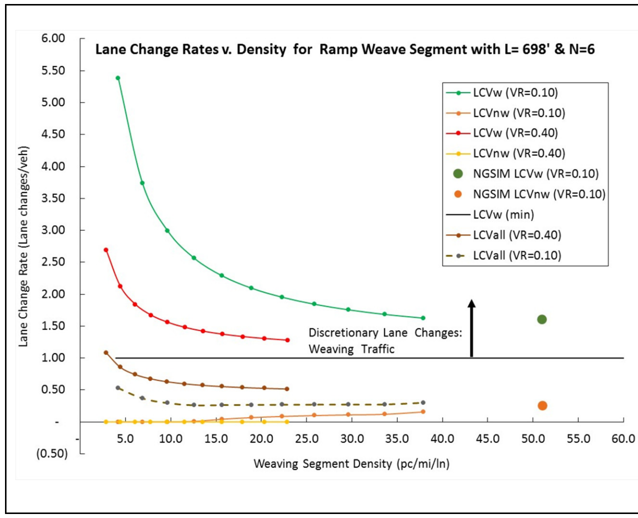

Figure 3. Sensitivity of lane change rates to segment density.

ratio exceeds 1. The US-101 site geometric attributes, along with the observed VR and other variables were input into the HCM6 procedure to generate the lane change rates for the corresponding undersaturated conditions. The total segment volume was allowed to vary to test the sensitivity of lane change rates to overall demand and the resulting density. This was done once with the volume ratio observed at the US-101site (VR˜0.10) and once with a much higher volume ratio (VR = 0.4). Those results are depicted in Figure 3.

The method first analyzes the emerging trends from applying the HCM6 procedure, noting that the ramp weave has a single auxiliary lane and thus $LCV_w^{min} = 1$. In both VR cases, the weaving lane change rate decreases with increasing density, perhaps because of the increasing scarcity of acceptable gaps in the neighboring lanes. The values on the low density side, however, appear to be excessive with close to 2 to 4 discretionary lane changes per weaving vehicle. On the other hand, the nonweaving lane change rates increase—albeit very slightly—with density, which is somewhat counterintuitive as one would expect the same density-restrictive effect to apply to both types of maneuvers. When combining all lane changes, the effect of density on lane change rates appears to be minimal, as the two trends essentially cancel each other out. For VR = 0.10 overall lane change rates varied from 0.3 to 0.5 per vehicle, and for VR = 0.4 they varied from 0.50 ~1.1 per vehicle (Figure 3).

With respect to the US-101 data, all observed lane changes occurred at lane densities exceeding 50 pcpmpl. Although there were three 15-min observations, the per-lane density during the entire 45-min period did not appreciably change (it varied from 49 to 52 pcpmpl) and therefore only the average condition is plotted in

Table 2. Count and Lane Changes by Movement Type in US-101 Dataset

Maneuver	Total vehicle count*	Total lane changes	Total LCV	Discretionary LCV
Weaving	484	775	1.60	0.60
Nonweaving	4,340	1,207	0.28	0.28

Note: *Count includes motorcycles in this table.

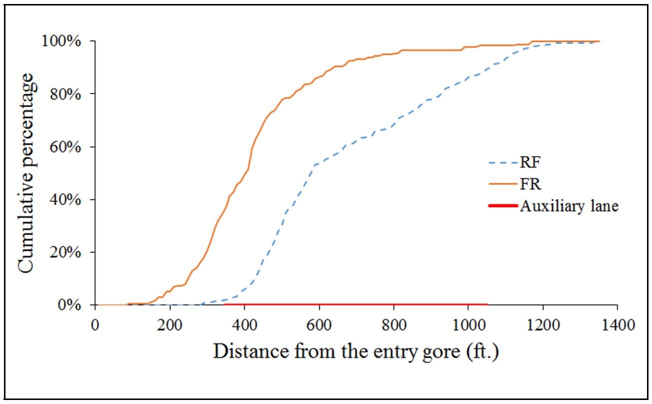

Figure 4. Cumulative distribution function (CDF) of lane change position (ft) for weaving vehicles.

Figure 3. Interestingly, the weaving lane change rate at the US-101 site appears to precisely follow the trend generated by the HCM6 model, confirming the earlier observation that the weaving lane change model and resulting weaving speed appear to be reasonable and match the empirical trend. Although one can make the same claim for the nonweaving rates based on visual observations in Figure 3, the sheer paucity of lane changes here and the counterintuitive trend generated by the HCM6 method makes this claim less plausible. One would, in fact, expect fewer discretionary lane change rates as density increases. Nevertheless, the US-101 dataset revealed that on average and under the observed congested conditions, the average weaving vehicle made 0.60 discretionary lane changes, compared with 0.28 lane changes for the average nonweaving vehicle.

Lane Change Patterns for the NGSIM Site

By Weaving Maneuver. Traffic in the NGSIM US-101 dataset can be characterized as highly congested. The reported SMS during the 45-min data extraction period varied from 21 to 30 mph, basically in the forced flow regime. In essence, a more severe downstream bottleneck affected the actual operation in the weaving segment. However, it should be noted that traffic speed on the auxiliary lane was significantly higher than that on the freeway lanes (*12*). These facts must be considered in interpreting the lane change rate analyses which follow. The categorization of trajectories into weaving and nonweaving vehicles across the three time intervals is shown in Table 2. As explained earlier, the volume ratio (VR) did not appreciably change during the 45-min observations, hovering around a value of 0.10. Therefore, the results presented here are aggregated over the entire 45 min. Weaving vehicles made an average of 1.60 lane changes, of which one lane change is mandatory. Nonweaving vehicles, on the other hand, made about 0.28 lane changes per vehicle, all of which are discretionary. As shown earlier in Figure 3, weaving vehicles had about twice the discretionary lane change rates as nonweaving vehicles at this congested site.

An important consideration in designing a ramp weave is to ensure it is long enough to enable both merging and diverging vehicles to execute their maneuver safely and at reasonably high speeds. The adequacy of the design can be assessed by tracking where those mandatory lane changes take place on the auxiliary lane. Tracking was done by measuring the position of the first point of contact for all lane changes between Lane 5 and the auxiliary lane (and vice versa). The zero distance was assumed to be the earliest feasible weaving point for freeway to ramp traffic. This point happened to be a fixed barrier about 346 ft upstream of the painted on-ramp gore. Recognizing that the US-101 site operates at very low speeds, the weaving length required to be operating at high speed can be somewhat relaxed for this dataset, as the entry and exiting vehicles speed differences were not appreciably lower than those observed on the freeway mainline. In Figure 4, two cumulative distribution functions (CDFs) of the distance from the first feasible weave point (for FR traffic) for each of the 484 weaving vehicles is depicted for freeway to ramp (FR) and ramp to freeway (RF) vehicles separately. Because a significant number of lane changes were observed upstream and downstream of the entry and exit gore marking, respectively, the physical separation between the auxiliary lane and Lane 5 is used as the start and end point in this plot.

Two important observations can be gleaned from the figure. First, over 50% of all lane changes at the start or end of the weaving maneuver were completed within the first 110 ft or about 16% of the short length. Second, about 90% of the FR weaves were completed in the first 630 ft of the total weaving length; that value was 1,060 ft for the RF

Table 3. Required Number of Lane Change Rates by Lane O-D for US-101

Required LCV by origin and destination lane	To 1	2	3	4	5	Auxiliary lane
From 1 (leftmost)	0	1	2	3	4	5
2	1	0	1	2	3	4
3	2	1	0	1	2	3
4	3	2	1	0	1	2
5	4	3	2	1	0	1
Auxiliary lane	5	4	3	2	1	0

Table 4. Discretionary Lane Change Rates by Lane O-D for US-101

Discretionary LCV by origin and destination lane	To 1	2	3	4	5	Auxiliary lane
From 1 (leftmost)	0.03	0.14	0.67	0.00	0.00	0.00
2	0.12	0.02	0.27	0.40	0.00	0.00
3	0.00	0.02	0.06	0.57	0.00	0.00
4	0.00	0.09	0.21	0.07	0.73	0.00
5	0.00	0.00	0.16	0.23	0.06	0.04
Auxiliary lane	0.00	0.11	0.12	0.19	0.14	0.00

Note: Shades of green, yellow, and red represent low, medium, and high values, respectively.

Table 5. Fraction of Vehicles Executing Discretionary Lane Changes by Lane O-D

Percentage vehicles by O-D	To 1	2	3	4	5	Auxiliary lane
From 1	1.50%	7.00%	33.50%	0.00%	0.00%	0.00%
2	6.00%	1.00%	13.50%	20.00%	0.00%	0.00%
3	0.00%	1.00%	3.00%	28.50%	0.00%	0.00%
4	0.00%	4.50%	10.50%	3.50%	36.50%	0.00%
5	0.00%	0.00%	8.00%	11.50%	3.00%	2.00%
Auxiliary lane	0.00%	5.50%	4.00%	9.50%	7.00%	0.00%

Note: Shades of green, yellow, and red represent low, medium, and high values, respectively.

traffic. That difference in auxiliary lane use could be attributed to the degree of perceived risk associated with the maneuver: missing the exit altogether for FR vehicles or waiting a bit longer for a mainline gap for the RF vehicles. In addition, the higher speed in the auxiliary lane than on the freeway lanes may motivate the FR vehicles to exit very early. However, during undersaturated conditions, there is no such motivation because speeds across lanes would not be vastly different. Therefore, the two distributions shown in Figure 4 may end up being similar under uncongested conditions, with the curve for RF shifting to the left and that for FR shifting to the right

By Lane to Lane Maneuvers. The next set of findings is aimed at answering two questions: how often and where are discretionary lane changes made, and to what extent are those "useful" to the drivers who execute them, presumably to save on their travel time. Based on the US-101 geometry in Figure 2, Table 3 gives the required number of lane change rates for any vehicle entering the weave in lane (i) and exiting it in lane (j). Table 4 gives the corresponding number of the observed discretionary lane change rates for each pair. Those are calculated as the actual number of lane changes made by each vehicle entering in lane (i) and exiting in lane (j) and subtracting the absolute value of $|j-i|$ from that number. In essence, adding the values in Tables 3 and 4 will give the total number of lane changes for each lane pair. As shown, the highest discretionary LCVs occurred for lane pairs 1–3, 3–4, and 4–5.

Another way to report the frequency of discretionary lane changes is to estimate the fraction of vehicles, for each lane pair, that are executing discretionary lane changes. For example, let us select the expected LCV for lane pair 3–4 above, which is 0.57. Here we assume that a fraction of vehicles (X) will make some discretionary lane changes, while the remaining $(100-X)$ will not, such

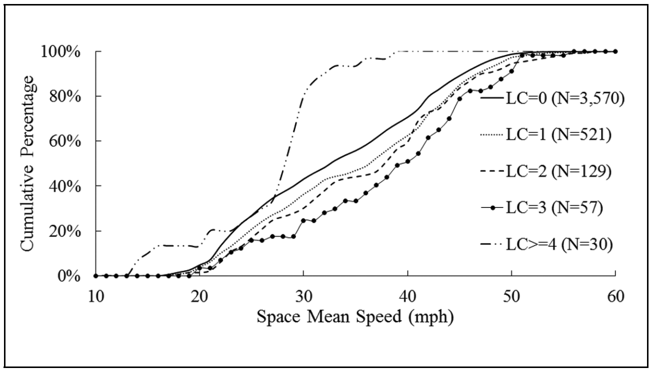

Figure 5. Cumulative distribution function (CDF) of space mean speed (SMS) for nonweaving vehicles by lane change frequency.

that the average per vehicle for that pair would be 0.57. Realizing that for pair 3–4 there are multiple lane paths that can be defined from Lane 3 to Lane 4, we confine the number of discretionary lane changes to two (note for any lane pair, and assuming that they exist, there will be a minimum of two discretionary lane changes). In our example, lane paths 3–2–3–4, or 3–4–3–4 are considered, each with two discretionary lane changes. Other paths while theoretically feasible such as 3–2–1–2–3–4, are ignored. Solving for $2X + 0 \times (100 - X) = 57\%$ yields $X = 28.5\%$. This value represents the fraction of vehicles entering Lane 3 which execute discretionary lane changes. The other 71.5% will only execute a single, required lane change. Those results are summarized in Table 5. Interestingly, the highest percentages are for vehicles moving further to the right lanes (e.g., 1–3, 2–4, 3–4 and 4–5) on the freeway mainline, perhaps for the purpose of utilizing the gaps created by those vehicles exiting the freeway.

Finally, we evaluate our hypothesis that discretionary lane changes are motivated by the desire to reduce travel time. Here only nonweaving vehicle lane changes are considered. Note here that the definition of "discretionary" is more relaxed than was described in the lane-based analysis; that is any lane change by a nonweaving vehicle is considered to be discretionary. The SMS across the weave, for each vehicle in that cohort, was computed. That speed was assigned to one of five bins, depending on whether that vehicle executed from zero to four or more discretionary lane changes. CDFs for the SMS are depicted in Figure 5. Those indicate that with the exception of the last cohort (for which the sample size is modest) the overall SMS distribution shifts to the right as the number of discretionary lane changes increases. As an example, the median speed for those vehicles making no lane changes is about 32 mph, compared with those making one (36.2 mph), two (37.9 mph) or three lane changes (39.9 mph). In effect, and with the caveat related to the four+ lane change cohort, evidence indicates that frequent lane changes on weaving segments pay off in relation to improved mobility for the drivers who execute them.

Summary and Conclusion

This study presented a critical assessment of the weaving segment analysis of HCM6 with respect to the inclusion of segment length in the methodology, and an analysis of lane change behavior during congested conditions. It investigated the sensitivity of lane changes and average speed of a weaving segment to the weaving segment length per HCM6 models. The variation of lane change rate at different density conditions is compared with that obtained from NGSIM's US-101 data. To aid in the comparison and investigation of lane changes, lane-based and vehicle-based performance metrics are proposed. In summary, the objectives of this study were twofold: (*a*) critically investigate the effect of weaving length on lane change and associated speed model estimates in HCM6, and (*b*) analyze trends in lane changes against congestion levels using detailed NGSIM trajectory data, and compare against HCM6 estimates.

For the first objective, and using a ramp weave example problem, this paper shows that because the nonweaving speed model is independent of segment length, nonweaving speed shows a trivial sensitivity to it. In fact, increasing the weaving segment length from 500 ft to 2,000 ft decreased the segment density only by 6.3%. For the second objective, the variation of weaving lane change rate with segment density follows an intuitive trend, decreasing with increasing density. However, the nonweaving lane change rate shows an increasing trend with density. When then compared with the NGSIM data, the lane change rate for weaving vehicles during congested conditions matched very well with the trend generated in HCM6. However, the same supposition could not be made with confidence for nonweaving vehicles because the HCM trend for nonweaving lane changes was found to be counterintuitive. This further puts into question the validity of the nonweaving lane change and speed models in HCM6

Further analysis of the NGSIM site data suggests that a significant amount of weaving vehicle lane changes occurred outside the short length of the weaving segment. In addition, most of the FR weaving vehicles changed lanes very early, while the RF weaves changed lanes almost uniformly over the entire segment.

The lane-based discretionary lane changes were identified for each O-D lane pair from the NGSIM data. The highest discretionary lane change rate occurred between Lanes 4 and 5 (5 being the rightmost freeway lane). It shows that about 36.5% of those vehicles executed discretionary lane changes. Overall, the average weaving vehicle had a 0.60 discretionary lane change rate at that site, compared with 0.28 for a nonweaving vehicle. While investigating the motivation of changing lanes by nonweaving vehicles, a speed analysis showed that in most cases more frequent lane changes yielded a higher SMS across the segment. The median speed for those making more than one lane change was 4 to 8 mph higher than for the no lane change cohort.

As a result of this work, several proposed research lines can be identified both to improve the HCM6 predictive power and to ascertain the effect of weaving length on LOS. Chief among those is a recalibration of the nonweaving lane change and speed models in HCM6 to achieve the expected trends, which were met for the weaving vehicles' models. Another line pertains to connecting capacity (or v/c ratio) to the HCM6 weaving method measures of effectiveness (MOEs), similar to their effect on basic freeway segments. Currently, capacity is only used to verify whether the segment is undersaturated before estimating the MOE, but is not included in the estimation. Finally, the relative volume of "weaving" traffic (FR versus RF) may need to be considered to see whether the weaving segment may effectively operate as an on-ramp or off-ramp segment if there is a high imbalance between those subweaving volumes. These lines of research are currently being explored in an ongoing project aimed at addressing the deficiencies in the current HCM6 methodology (*13*).

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Author Contributions

The authors confirm the following contributions to the paper: study conception and design: NR; data collection: DX, AK; analysis and interpretation of results: IA, DX, NR, AK; draft manuscript preparation: IA, NR. All authors reviewed the results and approved the final version of the manuscript.

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