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# Development of an appropriate model for the optional lane-changing rate in weaving segments with short lengths

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**KEYWORDS**
Weaving segment;
Density;
Lane-changing rate;
Regression model;
Weaving vehicles;
Non-weaving vehicles;
Highway Capacity Manual (HCM).

**Abstract.** To compute the level of service and density in weaving segments, the Highway Capacity Manual (HCM) defined for the first time in 2010 a relationship based on a lane change rate to assess the density of the weaving segment. It is critical to accurately estimate the lane-changing rates in these situations, but field observations in weaving segments shorter than 250 meters in Tehran, Iran revealed a significant difference between the HCM2022 model estimate and field data. The traffic and geometric data collected at 87 (15-minute) intervals from six weaving segments in Tehran were used to develop models for estimating lane-changing rates in weaving segments. These 87 intervals were then divided into 69 (terrain data) for equations and 18 (test data) for model comparisons. Weaving volume and weaving segment area are introduced as two independent variables in the optional lane-changing rate model of weaving vehicles in this study, with $R^2$=0.74. Furthermore, for a lane-changing model of non-weaving vehicles with $R^2$=0.95, two new variables of non-weaving volume and traffic solidity were defined. Finally, based on the 18 intervals used to test the results, it showed the improvement of the developed models' results compared to HCM2022 models.



## 1. Introduction

### *1.1. Background and motivation*

Weaving segments are among the most important segments that can affect the performance of an entire highway or freeway. There is a high level of turbulence in weaving segments due to lane changes of weaving and non-weaving vehicles. Such lane changes involve two parts, including mandatory and optional. Mandatory lane changes are made by weaving vehicles to enter the destination of drivers, such as the freeway, highway, or an off-ramp. Optional lane changes are made by both weaving and non-weaving vehicles to increase the speed or decrease the travel time of drivers.

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Some traffic and geometric parameters affect lane-changing of weaving and non-weaving vehicles. There is an equation for estimating the total lane-changing rate for weaving vehicles in HCM (Highway Capacity Manual) 2022. This equation consists of 2 parts: required (mandatory) lane changes equal to $LC_{MIN}$ and optional lane changes equal to the next term. The following equation is given below:

$$LC_W = LC_{MIN} + 0.39[(L_S - 300)^{0.5} N^2 (1 + ID)^{0.8}], \quad (1)$$

where $LC_W$= Equivalent hourly rate at which weaving vehicles make lane changes within the weaving segment (lc/h); $LC_{MIN}$= Minimum equivalent hourly rate at which weaving vehicles must make lane changes within the weaving segment to complete all weaving maneuvers successfully (lc/h); $L_S$= Length of the weaving segment, using the short length definition (ft) (300 ft is the minimum value); $N$= Number of lanes within the weaving segment (ln); and $ID$= Interchange Density (ID), the number of interchanges within 3 mi upstream and downstream of the center of the subject weaving segment divided by 6, in interchanges per mile (int/mi) [1].

Only geometric parameters such as $L_S$, $N$, and $ID$ are included as an optional part of the lane changes in Eq. (1). It seems, however, that traffic variables with geometric variables in equation1 together can better calculate the lane-changing rate of weaving vehicles (hypothesis of this study). Also, there are three Eqs. (13-13), (13-14), and (13-15) in HCM2022 for estimating the lane-changing rate of non-weaving vehicles based on $I_{NW}$ (non-weaving vehicle index) value. For example, for $I_{NW} \leq 1300$, Eq. (13-13) is used which is as follows:

$$LC_{NW1} = (0.206\ v_{NW}) + (0.542\ L_S) - (192.6\ N), \quad (2)$$

where $\nu_{NW}$ is the non-weaving flow rate and $LC_{NW1}$ is the rate of lane-changing per hour [1]. As in the previous case, field observation studies in Tehran, have shown that Eq. (2) could have some different new variables (such as $V_T$, which is the total volume in the weaving segment) to more accurately estimate the lane-changing rate of non-weaving vehicles.

It should be noted that it was not expected that the HCM2022 model would provide an accurate estimate of the lane-changing rate based on non-US traffic conditions. Therefore, the author has already known that if the HCM model is used, there would be a significant difference with field observations. This issue is also addressed in the international use section of HCM2022 Volume 1, Chapter 1. According to this, HCM users are cautioned that most of the research base, the default values, and the typical applications are from North America, particularly from the United States. Although there is considerable value in the general methods presented, their use outside of North America requires an emphasis on the calibration of the equations and procedures to local conditions and recognition of major differences in the composition of traffic; in driver, pedestrian, and bicycle characteristics; typical geometrics and control measures [1].

### *1.2. Research objectives and contribution*

This research follows the development of a lane-changing model for weaving segments based on the HCM2022 model and also on the above-mentioned hypothesis, where possible, to include some other variables in Eqs. (1) and (2). A more accurate and complete estimation of the lane-changing rate at weaving segments leads to improved highway and freeway operation (e.g., higher speeds and better LOS (Level of Service). Furthermore, there is no mention of new models for estimating lane-changing rates in weaving segments in previous studies such as Ishtiak Ahmed et al. [2] as a result, these models should be considered to fill the gaps in previous studies and improve the operation of weaving segments.

The main goal of the research is to define important effective variables on optional lane-changing rates of weaving and non-weaving vehicles for weaving segments with short lengths, and then use these variables to select a lane-changing model for traffic conditions of Iran. It should also be noted that the study's novelty is the discovery of new effective variables in the lane-changing rate of weaving segments.

### *1.3. Literature review*

On a global scale, traffic congestion on highways and freeways is recognized as a transportation challenge. Several studies have shown that creating bottlenecks is one of the primary limiting factors of highway traffic flow. A weaving segment can become a bottleneck during peak traffic intervals, worsening traffic congestion. A weaving segment is formed when a merge segment is closely followed by a diverge segment, and the traffic flows of these two areas become interconnected and create weaves, according to the HCM definition. Weaving segments cause a concentration of lane changes along highways, and the value of these lane changes affects the level of service provided by the highway. Lane changes in these segments are classified into three types: mandatory weaving vehicle lane changes, optional weaving vehicle lane changes, and optional non-weaving vehicle lane changes [1,2].

Significant research has been conducted on the issue of lane changing in weaving segments. Ishtiak Ahmed et al.'s research, in which the lack of sensitivity to weaving length was discovered to be related to the absence of this parameter in non-weaving lane change and speed models, is an essential relevant work. A comparison of HCM2016 lane change rates with

NGSIM, US-101 data confirmed that the HCM2016 weaving vehicle estimates are fully consistent with those at the NGSIM density control site [2]. Moreover, Ouyang et al. investigated the effects of configuration elements and traffic flow conditions on lane-changing rates at weaving segments. The HCM2016 procedure was initially used to estimate expected lane-changing rates and identify existing issues. Under the same traffic flow conditions, the model results showed that the Major-Weave II weaving segment had the fewest lane changes when compared to the other three types of weaving segments [3].

Mohajeri and Akbarzadeh conducted research on various HCM methodologies for the analysis of weaving segments, with a case study in Isfahan, Iran. The purpose of this study is to evaluate and compare the precision and effectiveness of models proposed in four recent editions of HCM (3rd to 6th). According to the results, the third edition performs best in estimating the speed of non-weaving vehicles on Iranian highways, edition six in estimating the rate of lane change, and edition five in estimating the rest of the variables and the level of service. As a result, a combined model is proposed that produces better results than the evaluated models [4]. These authors also conducted research on the evaluation of methods for computing FFS (free-flow speed) and its importance in HCM 2010. A comparison of the model results and the field data revealed that HCM 2010 method outperformed the other two methods for field measurement of FFS. Nonetheless, the HCM 2010 model's significantly poor performance in predicting the speed of non-weaving vehicles had a negative impact on the model's final outcome and resulted in under-predicted results. Therefore, the study proposed a novel method that produces significantly better results than other methods [5].

Many studies have been conducted on the capacity of weaving segments. Lertworawanich and Elefteriadou used a combination of analytical formulas and a gap acceptance and linear optimization model to predict the capacity of the weaving sections [6]. The methodology proposed expresses capacity as a function of the demands, the weaving vehicle ratios and the weaving and non-weaving vehicle speeds. A simple analytical model for evaluating the weaving section capacity is proposed in Rakha and Zhang study. The model contains three variables: the length of the weaving section, the volume ratio of the weaving section and the weaving ratio. This paper also showed the model being proposed is consistent with field data [7]. Roess and Ulerio have also conducted research focusing on determining the analytical expression of the capacity of a weaving segment [8]. Also, the models developed by Roess and Ulerio were based on short-term traffic data but with a variety of road characteristics to predict the capacity and speed of a weaving segment. The models were included in HCM2010 and were retained in HCM2016 [9]. A weaving segment's relationship between speed and ramp spacing was investigated using video record data from seven weaving segments in Texas, and using a linear regression model. It has been shown that the operating speed of the weaving segment could be modeled on the basis of the total exiting volume, the ratio of the ramp to the ramp volume to the total entry volume, and the length of the segment [10]. Moreover, Xu et al. investigated a modeling framework for capacity analysis of freeway ramp weave segments, proposing two models for estimating the capacity and speeds of weaving segments. In terms of explaining field speed observations as well as application simplicity, these models outperformed HCM2016 models. The findings include a new capacity estimation formula that is highly sensitive to segment length and a speed estimation model that converges to that observed at a basic segment for low weaving volumes or very long weaving segment lengths [11].

Some research has been conducted on driving behavior at weaving segments. To evaluate the position of mandatory lane changes and the resulting turbulence in a weaving section, trajectory data collected from airborne videos were used [12,13]. The data collected by Marczak et al. was limited to a single weaving site, showing that the weaving vehicles completed all mandatory lane changes within the first 60% of the segment's total length [12]. Van Beinum et al.'s data came from 8 weaving sites, but the findings were close to those Marczak et al. had collected. It was found that, within the first 25% of the total length, about 65% to 95% of weaving lane changes occurred [13]. In another study, Yuan et al. investigated drivers' mandatory lane change behavior on a weaving section of the motorway with managed lanes, with the goal of determining the safety effects of weaving length, traffic conditions, and driver characteristics on drivers' mandatory lane change behavior [14].

Also, studies on the mechanism of lane changing at weaving segments have been conducted. A detailed trajectory analysis revealed that a significant proportion of the lane-changing at the weaving section exhibited group lane-changing behavior, in the form of a lane-changing platoon and simultaneous weaving behavior in the Kusuma et al. study. The findings suggested that the relative speed of the current and target lane leaders had varying effects on gap acceptance behavior [15]. Also, using microscopic traffic data, Chauhan et al. conducted research on the mechanism of lane-changing process and dynamics. Two types of classification are considered in the study: free lane change and constraint lane change, and the lane change duration for these two types is fitted with a log-normal distribution [16].

Furthermore, in terms of bottlenecks in weaving segments, Cassidy and Lee [17] and Skabardonis and Kim [18] conducted macroscopic empirical analyses to define bottleneck activation for two weaving sections. The authors used oblique cumulative vehicle counts from loop detectors located within the weaving zone at a distance of 400 m (first site) or 500 m (second site). Cassidy and Lee concluded that the bottleneck activation at both weaving sections was triggered by disruptive freeway to the ramp lane changes [17]. They also explained that in the discharge flow, the position of the lane changes from the highway to the ramp along the weaving segment play a role. To complete this overview of empirical data analysis, Sarvi et al. presented a very small sample of microscopic data. The authors concluded, however, that the vehicles surrounding the freeway significantly affect the acceleration behavior of the weaving vehicles [19].

Moreover, much research has been conducted on lane changing in the context of connected and autonomous vehicles. Hou et al. investigated the factors that influence the length of the lane-changing buffer zone for autonomous driving dedicated lanes. This study uses NGSIM data to filter out typical lane-changing description data containing lane-changing behaviors and builds a Principal Component Analysis (PCA) model containing factors affecting the longitudinal driving distance throughout the entire lane-changing procedure. The length of lane-changing buffer zones is suggested by comparing the PCA model to a general linear regression model [20].

Furthermore, studies on simulation in traffic issues have been conducted. Traffic modeling and simulations are indispensable in transportation infrastructure planning. Many research projects focus on designing road networks and intersections, analyzing traffic situations to eliminate congestion, reducing vehicle delays, and improving road safety. The majority of them are based on the development and analysis of microscopic models. In the study by Yuniawan et al., a method of simulation was used to manage the traffic queue. Arena Simulation software was used to simulate the traffic queue line [21,22]. Moreover, simulation has been used to assess traffic safety, as detailed in a reference [23].

### *1.4. Modelling approach*

As stated in background and motivation, the objective of this research is to develop a model for lane-changing rates in which traffic and geometric variables are used simultaneously. Furthermore, field observations have shown that the lane-changing rate predicted by the HCM2022 equations is underestimated for Iran's traffic conditions.

Data from this study is extracted based on filming from 6 weaving segments in Tehran, Iran for 87 15-minute periods. Required geometric parameters including weaving segment length ($L_s$) and ID as well as traffic parameters such as volumes of different maneuvers, Space Mean Speed (SMS) of 40 weaving and non-weaving vehicles in each 15-minute period, and finally, all optional lane changes of weaving and non-weaving vehicles have been carefully obtained. New regression models have been developed based on the above-mentioned data. Subsequently, the validity of these models was checked based on statistical tests and, finally, they were compared with HCM2022 models and field observations.

### *1.5. Scope of the study*

There are two limitations to this research. The first is that, this study was conducted for the city of Tehran in Iran, and the new models obtained are based on Tehran traffic conditions. The second is about the length of the weaving segments, which were all less than 250 m. Furthermore, the new models are restricted to one-sided weaving segments with $N_{wl} = 2$. The posted speed limit on the studied weaving segments was 80 km/h for the North Imam Ali and Jalal-e-Al-e-Ahmad Highways and South Sheikh Fazlollah Nuri Expressway, and 90 km/h for the junction of the West and East Hemmat Expressways with the Imam Ali Highway. Besides that, the density of the studied weaving segments was mostly in the 28-43 pc/mi/ln range (LOS D and E).

## 2. Methodology

The steps of this study are shown on the flowchart below in Figure 1.

Here is a brief explanation of the steps in the flowchart above. The required traffic and geometric data were obtained in Step 1. In Step 2, the field data collected and the specifications of the six weaving segments studied are given in two tables. The control of the correlation values between possible variables was checked in Step 3. The optional lane-changing models have been produced in Step 4 using SPSS software. The estimation of new test models, such as the coefficient of determination and the probability value, was carried out in Step 5. If the tests were acceptable, Step 6 will continue, otherwise, the variables should be reviewed. In Step 6, two statistical tests were used to check the homogeneity and normality of the residuals of the two new models. If these two tests have acceptable values, then Step 7 will continue, otherwise we should go back to Step 4 and produce new models with different variables. Finally, the new models were compared with the HCM2022 models and field observations in Step 7 in terms of tables and figures.

Table 1 shows a sample of field data collected from weaving segment number 1. It should be noted that data from other weaving segments has been omitted

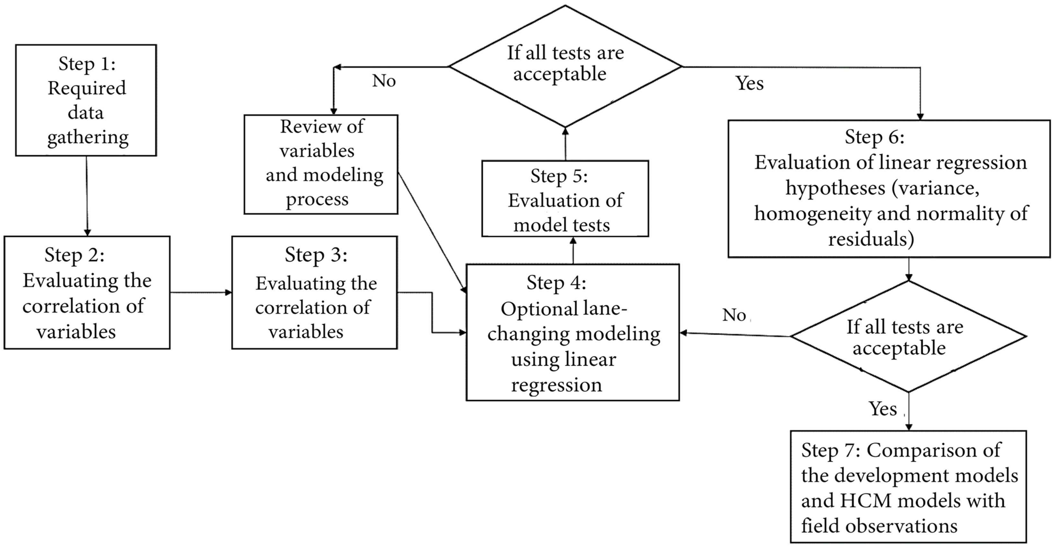


**Figure 1.** Flowchart of the analytical and experimental research of the study.

**Table 1.** Sample field data collected from weaving segment number 1.

| $L_S$ (m) | $N_T$ | $N_O$ | $N_A$ | $V_T$ (pc) | $V_{NW}$ (pc/h) | $V_W$ (pc/h) | $VR$ | $LC_{OT}$ | $LC_{OW}$ | $LC_{NW}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 230 | 5 | 3 | 2 | 8232 | 5532 | 2700 | 0.33 | 1848 | 1072 | 776 |
| | | | | 8292 | 6296 | 1996 | 0.24 | 1892 | 988 | 904 |
| | | | | 8112 | 5780 | 2332 | 0.29 | 1456 | 748 | 708 |
| | | | | 7044 | 4564 | 2480 | 0.35 | 1224 | 508 | 716 |
| | | | | 8672 | 6108 | 2564 | 0.30 | 1808 | 960 | 848 |
| | | | | 6012 | 4064 | 1948 | 0.32 | 1900 | 1164 | 736 |
| | | | | 7612 | 5672 | 1940 | 0.25 | 1864 | 992 | 872 |
| | | | | 8204 | 6340 | 1864 | 0.23 | 2040 | 1068 | 972 |
| | | | | 7868 | 5848 | 2020 | 0.26 | 2008 | 952 | 1056 |
| | | | | 8240 | 5936 | 2304 | 0.28 | 1900 | 884 | 1016 |
| | | | | 8264 | 6112 | 2152 | 0.26 | 1816 | 692 | 1124 |
| | | | | 8040 | 5552 | 2488 | 0.31 | 1628 | 772 | 856 |

from the table due to a lack of space. In this table, $L_s$ is the length of the weaving segment in meters (using the short length definition), $N_T$ is the total number of lanes, $N_O$ is the number of main lanes and $N_A$ is equal to the number of auxiliary lanes. $V_T$, $V_{NW}$, and $V_W$ are showing total, non-weaving, and weaving volumes in the weaving segment. $VR$ is the volume ratio equal to $V_W$ over $V_T$. Finally, $LC_{OT}$ and $LC_{OW}$ indicate the total and weaving optional lane changes and $LC_{NW}$ shows non-weaving lane changes counted in the 6 weaving segments studied. It should be noted that these optional lane changes for weaving and non-weaving vehicles are counted in the six weaving segments based on lane changes per vehicle and not per hour. There have been some other data, such as the speed of 40 non-weaving vehicles and $LC_{\min}$ (the minimum rate at which weaving vehicles must change lanes to complete all weaving maneuvers successfully) that have been omitted from the table due to lack of space and low significance in doing this study.

## 3. Data collection

To collect data for modeling, six weaving segments in Tehran, Iran was selected. These weaving segments with allocated numbers, the number of 15-minute data collection periods for each of these segments, their latitude and longitude, and their lengths are shown in

**Table 2.** Specifications of all six studied weaving segments.

| Weaving segment number | Number of 15-minute data collection periods | Latitude and longitude | Weaving length (meters) |
|---|---|---|---|
| 1 | 16 | 35°43'44.2"N<br>51°22'06.8"E | 230 |
| 2 | 14 | 35°45'31.4"N<br>51°29'04.8"E | 180 |
| 3 | 15 | 35°45'32.5"N<br>51°29'03.7"E | 150 |
| 4 | 16 | 35°45'06.1"N<br>51°31'54.2"E | 190 |
| 5 | 15 | 35°44'57.4"N<br>51°22'18.3"E | 110 |
| 6 | 11 | 35°45'31.6"N<br>51°29'06.0"E | 150 |

Table 2.

The data was collected between the end of December 2019 and the end of February 2020. It was carefully recorded by filming from elevated locations and mostly footbridges close to the weaving segments. The required data is divided into two categories: geometric data and traffic data. Field observations and Google Maps were used to collect geometric data such as the number of lanes and the lengths of weaving segments. For traffic data, data from recorded videos of traffic situations in six studied weaving segments (video processing) were analyzed. As an example of traffic data, consider the collection of weaving and non-weaving speed data.

The average speed of weaving and non-weaving vehicles in recorded 15-minute time intervals is used to calculate the speeds of weaving and non-weaving vehicles. The speeds are measured in kilometers per hour SMS was used to collect speeds in the field. SMS is calculated using the traversed length as well as the vehicles' arrival and departure times in the subject weaving segment. The speed of 40 weaving and non-weaving vehicles is collected for each 15-minute time interval and the average is presented as the speed of weaving and non-weaving vehicles in the subject time period.

The extracted data contains the following items:

1. Traffic volumes including freeway to freeway, freeway to ramp, ramp to freeway, and ramp to ramp;
2. SMS of weaving and non-weaving vehicles (40 vehicles for each at 15-minute time periods);
3. Optional lane changes of weaving and non-weaving vehicles;
4. Other information, such as ID, weaving segment length, and number of lanes, is extracted from google maps.

## 4. Data analysis

The field observed lane change rates in some of the weaving segments studied in Tehran differ significantly from the expected values of HCM2022. Information on lane changes in the six weaving segments for 3 hours has been collected for each segment. Figures 2a and 2b show the average, maximum, and minimum percentage of the absolute difference between the observed and HCM2022 optional lane change values for weaving and non-weaving vehicles in all six weaving segments studied in Tehran over a 3-hour period.

It should be noted that the percentage difference shown in Figures 2a and 2b is the ratio of observed values minus HCM over observed values of optional lane changes, which are then multiplied by 100. As can be seen from both figures above, HCM2022 underestimates the rate of optional lane change for both weaving and non-weaving vehicles, and the percentage difference values are noticeable. It is also clear that the average, maximum, and minimum values for non-weaving vehicles are more than for weaving vehicles. This is due to the lower calculated lane change values of HCM2022 for non-weaving vehicles (in some cases below, equal to or close to zero) which resulted in higher difference values with field observations. The highest maximum difference percentage is for weaving segment 3 equal to 95% for non-weaving vehicles.

As a result of the figures, it is necessary to produce new models for estimating the total lane changes rate of weaving and non-weaving vehicles.

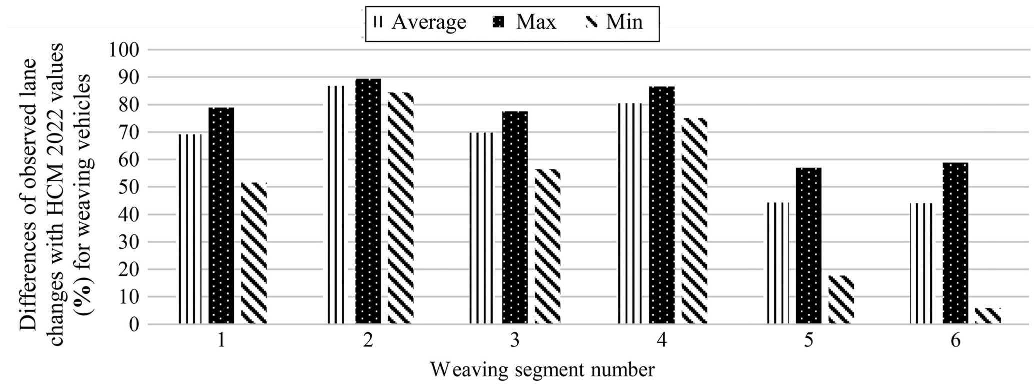


**Figure 2(a).** Absolute difference values (%) of optional lane changes for weaving vehicles.

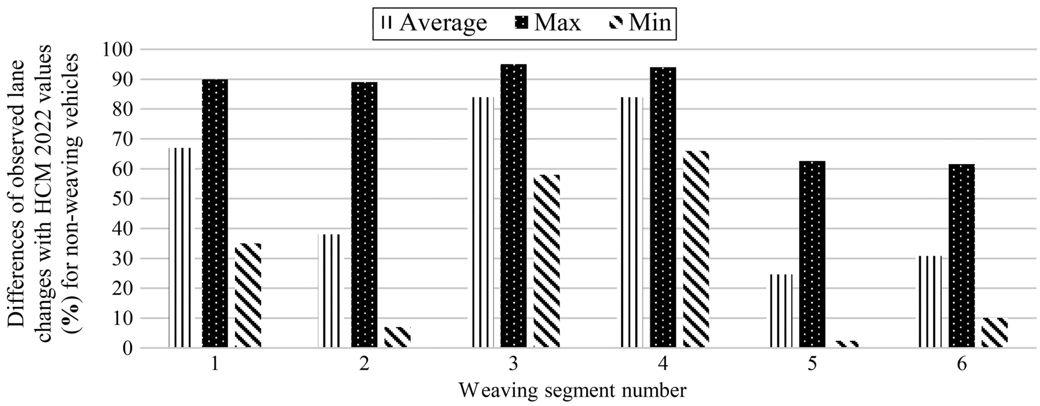


**Figure 2(b).** Absolute difference values (%) of optional lane changes for non-weaving vehicles.

## 5. Modeling and results

After data analysis, data including new variables were entered into SPSS software to obtain a new model for estimating the total lane change rate for weaving and non-weaving vehicles. Models were produced using 69 out of a total of 87 available data (15-minute periods). The remaining 18 periods, equivalent to 20% of the total data collected, have been used to evaluate the results of the developed models and to compare them with the HCM 2022 equations.

It should be noted that, before obtaining Eq. (3), the author attempted to produce an equation with similar variables to HCM2022 ($L_s$, $N$, $1+ID$) for the optional lane-change rate of weaving vehicles. However, it was found that the correlation between $L_s$ and $N$ is 0.67 and the correlation between $1+ID$ and $N$ is 0.6, both of which are high. This issue indicates that these variables cannot be used in an equation together. Table 3 shows the correlation values for all three variables in the HCM equation. It was therefore impossible to re-calibrate the HCM model (Eq. (1)) for Iran's traffic conditions.

To validate the new generated models, the correlation between all the variables used in these two models should be controlled before the regression models developed for the lane-changing rate of weaving and non-weaving vehicles are introduced. As a consequence, Table 4 below shows the correlation of variables.

The variables used in Table 4 are in abbreviation form, so it is necessary to provide a clear description for each of them. $LC_{OW}$ and $LC_{NW}$, which are dependent variables, indicate optional lane changes for weaving vehicles and lane changes for non-weaving vehicles, respectively. $V_{NW}$ and $V_W$ stand for non-weaving and weaving volumes. The combined variable $L_S$. $N_T$ is the multiplication of $L_s$ and $N_T$, which are the weaving length and the total number of lanes in the weaving

**Table 3.** Correlation values between parameters of HCM equation.

| | $L_s$ (m) | $N$ (number of lanes) | $1+ID$ |
|---|---|---|---|
| $Ls$ (m) | 1.00 | 0.67 | 0.12 |
| $N$ (number of lanes) | 0.67 | 1.00 | 0.60 |
| $1+ID$ | 0.12 | 0.60 | 1.00 |

**Table 4.** Correlation of all variables used in weaving and non-weaving models.

| | $V_{NW}$ | $V_W$ | $LC_{OW}$ | $LC_{NW}$ | $L_S.N_T$ | $D_{V/A}$ |
|---|---|---|---|---|---|---|
| $V_{NW}$ | 1 | −0.04 | 0.03 | 0.91 | 0.73 | −0.03 |
| $V_W$ | −0.04 | 1 | 0.75 | −0.09 | 0.22 | −0.31 |
| $LC_{OW}$ | 0.03 | 0.75 | 1 | 0.01 | 0.39 | −0.57 |
| $LC_{NW}$ | 0.91 | −0.09 | 0.01 | 1 | 0.79 | −0.2 |
| $L_S.N_T$ | 0.73 | 0.22 | 0.39 | 0.79 | 1 | −0.69 |
| DV/A | −0.03 | −0.31 | −0.57 | −0.2 | −0.69 | 1 |

**Table 5.** Summary of selected optional lane-changing model for weaving vehicles.

| Parameters | Coefficients | $p$-values | $t$-test | $R^2$ | $F$-statistic | Residual standard error |
|---|---|---|---|---|---|---|
| Intercept | −17.1969 | $1.12e-11^{***}$ | −8.208 | | | |
| $L_n V_w$ | 2.3720 | 1.70e-11 *** | 8.107 | 0.7398 | 97.64 | 0.3438 |
| $L_n L_s N_T$ | 0.8400 | 2.63e-10 *** | 7.442 | | | |

*** The qualitative significance level of the coefficients which relies on the $p$-value.

segment. Finally, $D_{V/A}$ ($V_T/L_s * N_T$) is equal to the total volume over the multiplication of $L_s$ and $N_T$.

According to Table 4, $LC_{OW}$ has a high correlation with $V_W$ and a fairly good correlation with $L_S.N_T$, which are the variables used in the lane change of the weaving vehicle model (Eq. (3)). These two independent variables also have a low correlation value (0.22) with each other, so they can be used together in a model. In the case of a non-weaving model, it can be seen that $LC_{NW}$ has a very high correlation with $V_{NW}$ (0.91) and a relatively good one with $D_{V/A}$. These two independent variables also have a very low correlation (−0.03) with each other, which means that there will be no problem using both of them together in a model.

The modeling process can be started after controlling the correlation of variables used in the models. Field data and all required variables for modeling have been entered into SPSS software. The first case concerns the lane change model for weaving vehicles. As previously stated, the model is obtained by using 80% of the total data (terrain data). The results of the acceptable model chosen in this case are shown in Table 5.

It should be noted that the model should be non-linear for weaving vehicles in accordance with Eq. (13–11) of HCM2022, so a non-linear logarithmic model (one of the simplest non-linear models) for optional lane changes of weaving vehicles has been produced in this research. In fact, the coefficient values are equal to the power amounts of the parameters shown in Table 5. The $R^2$ value according to Table 5 is high enough to accept the model and also the $p$-values of all parameters are less than the allowable amount (0.05) indicating the validity of the model. The equation derived from this model is therefore as follows:

$$LC_W\ (optional) = (3.85 \times 10^{-8}) \times [V_w^{2.37} \times (L_s \times N_T)^{0.84}]. \qquad (3)$$

According to Eq. (3), the model developed for estimating optional lane changes of weaving vehicles includes independent variables: weaving volume, weaving length, and total number of lanes used as a weaving segment area criterion by the product of variable length and number of lanes. As shown in Eq. (1) (Eq. 13–11), HCM2022), the independent variables of the number of lanes and the length of the weaving segment were two effective variables for the optional lane changes rate of weaving vehicles and have a direct relationship with it, which also exists in this study.

In HCM2022 model, the optional lane changes rate of the weaving vehicles has no relation to traffic conditions and volumes and depends only on geometric variables, hence the weaving volume, which is a traffic variable and defines the level of traffic flow, has been used in the development of this model (Eq. (3)). This variable has a direct relationship with the number of optional lane changes and an increase in weaving volumes leads to an increase in optional lane changes made by weaving vehicles. The result seems rational for the number of weaving vehicles to have a significant impact on the lane change rate.

To verify the validity of the model obtained, it is necessary to check the equality of the error variances and the normality of the residuals, which are the two assumptions of the regression model. There are two tests to control these two items: Shapiro-Wilk test for residual normality and Breusch-Pagan test for variance equality. For interested readers, the basics and fundamentals of these two tests can be found in three Refs. [24–26]

Table 6 shows the $p$-values of Shapiro-Wilk and Breusch-Pagan tests for Eq. (3).

Based on Table 6, both $p$-values are greater than 0.05, which means that residual normality and variance equality assumptions are accepted, hence Eq. (3) will be approved.

The assessment of optional lane change rates for weaving vehicles calculated from HCM2022 model and Eq. (3) in this study was compared with field observations in Figure 3.

As can be seen in Figure 3, HCM underestimates the optional lane change rates of weaving vehicles, whereas the model (Eq. (3)) estimate is so close to field observations. The maximum difference between the developed model and field observation is equal to 273 lc/hr in the 12th data, while this value for HCM and field observations is equal to 1102 lc/hr in the 14th random data in Figure 3. Consequently, the developed model is way more accurate than HCM according to the traffic conditions of six weaving segments studied in Tehran, Iran.

To evaluate the model developed, the value and percentage of the difference in field observations with HCM2022 and the model were calculated. The Root Mean Square Error (RMSE) is also used to display the improvement of the developed model compared to the HCM2022 model. Table 7 shows these values that were obtained using test data.

**Table 6.** Results of Shapiro-Wilk and Breusch-Pagan tests for Eq. (3).

| **Test name** | ***p*-value** |
|---|---|
| Shapiro-Wilk | 0.605 |
| Breusch-Pagan | 0.962 |

According to Table 7, the results obtained from the developed model of optional lane changes for weaving vehicles show an improvement in the estimation relative to HCM2022 model. Accordingly, the RMSE was reduced up to 600 units and was equal to approximately 80% in the developed model:

$$\left( RMSE = \sqrt{\frac{\sum_{i=1}^{n} \left(x_{i,\text{model}} - x_{i,\text{observed}}\right)^2}{n}} \right).$$

The absolute mean value of the difference in the developed model was also reduced up to 530 units and equal to 80%, which indicates an improvement in the results of this model. Another important point is the underestimation of the optional lane changes rate of the weaving vehicles by HCM2022 equation, as said in the explanation of Figure 3.

The second case concerns lane changes of non-weaving vehicles. The model in this case was developed using the linear regression approach and the SPSS software for weaving segments with short lengths (less than 250 m) using terrain data. The results of the model developed have been shown in Table 8 and the new equation is shown as Eq. (4) below Table 8:

$$LC_{NW} = (0.16 \times V_{NW}) - \left(19.42 \times \frac{V_T}{L_S \times N_T}\right). \quad (4)$$

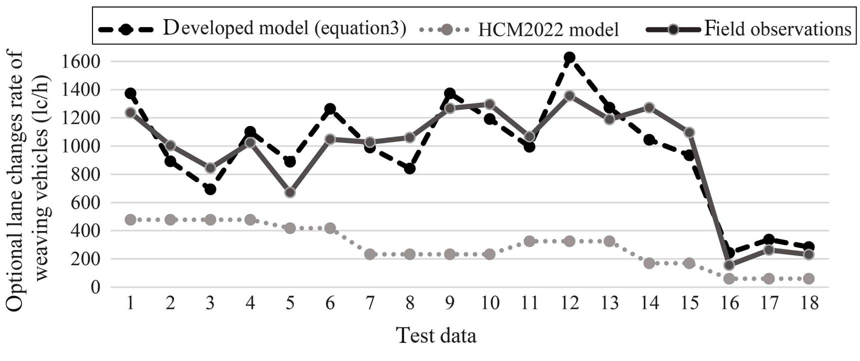


**Figure 3.** Comparison of optional lane changes rate of weaving vehicles.

**Table 7.** Evaluation of estimation results of optional lane changes rate of weaving vehicles by the developed model and HCM2022 model.

| **Model** | **Criterion reviewed** | | |
|---|---|---|---|
| | **RMSE** | **Absolute average percentage of differences** | **Absolute mean value of differences** |
| HCM2022 model | 737 | 68.3 | 6637 |
| Developed model | 150 | 17.5 | 134 |

**Table 8.** Summary of selected optional lane-changing model for non-weaving vehicles.

| Parameters | Coefficients | $p$-values | $t$-test | $R^2$ | $F$-statistic | Residual standard error |
|---|---|---|---|---|---|---|
| $V_T/(L_S \times N_T)$ | $-19.4233$ | $1.48e-07^{***}$ | $-5.872$ | 0.9522 | 688.5 | 114.8 |
| $V_{NW}$ | 0.1617 | $< 2e-16^{***}$ | 22.767 | | | |

$^{***}$The qualitative significance level of the coefficients which relies on the $p$-value.

Based on Eq. (4), the lane change rate of non-weaving vehicles is associated with two independent variables, including the non-weaving volume and solidity of the weaving segment. In this equation, increasing the non-weaving volume is expected to increase the rate of lane changes in non-weaving vehicles seen in the HCM2022 developed models.

Another variable of Eq. (4) is the solidity of the weaving segment, which has an indirect relationship to the lane change rate of non-weaving vehicles. This variable consists of the total volume, the total number of lanes, and the length of the weaving segment. According to the HCM2022 model, the lane change rate of non-weaving vehicles has an indirect relationship with the number of lanes and a direct relationship with the weaving length of the segment. Given that the range of weaving length changes in this study is much more limited than in HCM2022 (HCM range includes lengths equal to almost 100 to 800 m, which is limited to the range of 100 to 250 m in this study), length has not been used as an independent variable and, on the other hand, this variable has a correlation with non-weaving volume.

On the other hand, the total number of lanes has a correlation with the non-weaving volume, so two variables of length and number of lanes of the weaving segment mentioned in HCM2022 cannot be used directly in Eq. (4). Thus, to see the impact of these variables, a new variable called solidity has been defined which shows the number of vehicles per meter in each lane. Increasing the density of the weaving segment leads to a reduction in vehicle maneuverability and therefore does not allow vehicles to change the lane easily. As a result, the number of lane changes of non-weaving vehicles seen in the model (Eq. (4)) is decreasing.

**Table 9.** Results of Shapiro-Wilk and Breusch-Pagan tests for Eq. (4).

| Test name | $p$-value |
|---|---|
| Shapiro-Wilk | 0.747 |
| Breusch-Pagan | 0.083 |

As in the previous case, before obtaining Eq. (4), the author tried to produce an equation with variables equal to the HCM2022 equation ($Vnw$, $Ls$, $N$) for the lane-changing rate of non-weaving vehicles. But it was found that these variables were highly correlated. The re-calibration of the HCM2022 model (Eq. (2)) was impossible under Iran's traffic conditions.

To accept the model obtained, it is necessary to check the equality of variance and the normality of residuals. Table 9 displays the $p$-values for the Shapiro-Wilk and Breusch-Pagan tests for Eq. (4).

Based on Table 9, both $p$-values are greater than 0.05, which implies that residual normality and variance equality assumptions are accepted, and thus Eq. (4) is approved.

Figure 4 shows a comparison of the lane change rates of non-weaving vehicles calculated by HCM2022 and the model developed in this study with field observations.

As in the previous case, it can be seen in Figure 4 that HCM underestimates the lane change rates of non-weaving vehicles and has significant differences

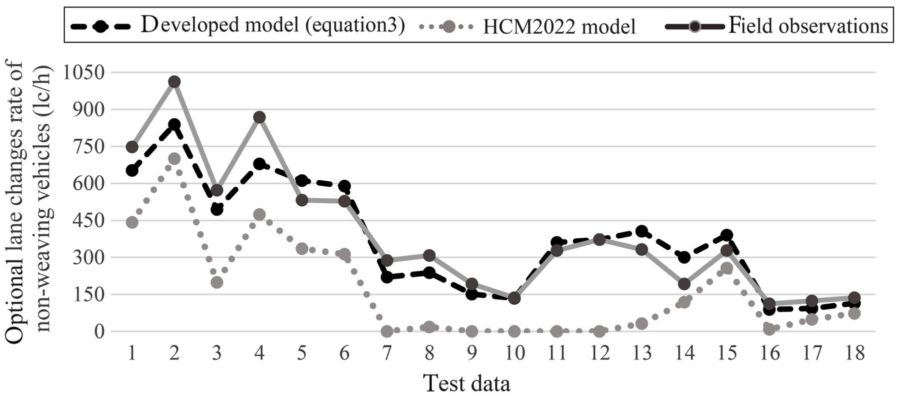


**Figure 4.** Comparison of lane changes rate of non-weaving vehicles.

**Table 10.** Evaluation of estimation results of lane changes rate of non-weaving vehicles by the developed model and HCM2022 model.

| **Model** | **Criterion reviewed** | | |
|---|---|---|---|
| | **RMSE** | **Absolute average percentage of differences** | **Absolute mean value of differences** |
| HCM2022 model | 254 | 66.9 | 227 |
| Developed model | 84 | 18.3 | 67 |

with field observations. Although the developed model behaves similarly to field observations, the differences are much smaller than in HCM2022. The maximum difference between the developed model and field observation is related to the 4th data and is almost 190 lc/hr. While this difference for HCM2022 is equal to 394 lc/hr in 4th random data. The developed model is therefore more accurate than HCM2022 model.

The value and percentage of difference in field observations with HCM2022 and the model were computed to evaluate the model developed. The RMSE is also used to show the improvement of the developed model compared to the HCM2022 model. These values, obtained from test data, are shown in Table 10.

According to Table 10, the results obtained from the developed lane change model for non-weaving vehicles indicate an improvement in the estimation relative to the HCM2022 model. Based on Table 10, the RMSE is reduced up to 170 units and is equal to 65% in the developed model compared to the HCM2022 model. The absolute mean difference between the developed model and the HCM2022 model with field observations indicates a decrease of 160 units (equal to 70%) in the developed model relative to HCM2022 model. Another important point is the observation of underestimation in the evaluation of non-weaving vehicle lane change rates by HCM2022 relative to field observations. The collection of this evidence and considerations on the available experimental sample shows an improvement in the results of the developed model in the estimation of lane change rates for non-weaving vehicles compared to HCM2022 model.

## 6. Conclusion

Based on the hypothesis of this study, it was found that traffic variables were also effective under the conditions of this study and that the effect was significant. When these variables were used, the error of comparison with field observations was significantly reduced compared to the state in which these variables were not used. It should also be noted that the models used in this study were based on weaving segments with lengths less than 250 m and traffic and geometric data collected in Tehran, Iran, which could be considered the limitations of the study.

The conclusion can be stated as follows, according to the findings of the study:

1. The new variable of the lane-changing new model for non-weaving vehicles, defined as traffic density, has an indirect relationship to the lane-changing rate of non-weaving vehicles. The reason for the relationship (indirect) is that by increasing the density of the weaving segment, the maneuverability of vehicles reduces and does not allow them to change lanes easily due to shorter vehicle gaps. The subject has been seen in the model;
2. It was found that changing the weaving volume did not affect the optional lane-changing rate of the weaving vehicles under constant conditions, which is illogical. This issue may be due to not including traffic variables in the Highway Capacity Manual (HCM) equation, and the need to include traffic variables is clear here. One of the issues that arises from this is that the results of the HCM model are not consistent with field observations and underestimation was observed for the conditions of this study;
3. For both lane-changing models of weaving and non-weaving vehicles, the multiplication of weaving length and the total number of lanes ($L_S \times N_T$) as the weaving segment area are included in Eqs. (3) and (4). As this area increases, vehicles will have more space and freedom to change lanes increasing the number of lane changes for weaving and non-weaving vehicles. In addition, increases in the fraction $V_T/L_S \times N_T$ have a negative effect on non-weaving vehicle lane-changing, as indicated by the minus sign in Eq. (4).

The results of this study revealed that the lane-changing rate in weaving segments computed by HCM2022 equations is underestimated for both weaving and non-weaving vehicles. In contrast, a comparison of HCM2016 lane change rates with NGSIM, US-101 data in the study of Ishtiak Ahmed et al. [2] indicated that the HCM2016 estimates for weaving vehicles are totally consistent with those at the NGSIM site, controlling for density. This matter should be thoroughly considered.

Furthermore, according to Akbarzadeh and Mohajeri's study titled "Appraisal of different HCM methodologies for the analysis of weaving segments, case study: A weaving segment in Isfahan, Iran," HCM2016 outperforms all other HCM editions in estimating the rate of lane change in weaving segments on an Iranian freeway. However, the study did not propose a model for weaving and non-weaving vehicle lane changing on a weaving segment. Instead, there were only two models for weaving and non-weaving vehicles. As a result, this research, which proposed models of lane changing in weaving segments, can be used to supplement the previous study.

The development of models for longer-length weaving segments may be an issue to be studied. Based on the focus of this research on short weaving segments (less than 250 m), another model can be developed by collecting data on longer weaving segments. It is also suggested that, since HCM was developed in the USA, using field observations in that country, the new regression models of this paper can be examined to consider the suitability of these models and their new variables for US traffic conditions.

Moreover, the use of connected and autonomous vehicles in weaving segments could be an interesting topic to research. In a relevant study, the system capacity, average length of the service queue, and average number of transport tasks for autonomous vans were all determined using mathematical modeling based on Markov random system theory [27].

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### Data availability statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request (one R script file for the produced equations of this research and some Excel files for the traffic and geometric data collected from 6 weaving segments in Tehran, Iran).

### Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

### Author contributions

The authors confirm their contribution to the paper as follows: study conception and design: Behrooz Shirgir, data collection: Shervin Sayyar, analysis and interpretation of results: Behrooz Shirgir, Shervin Sayyar, draft manuscript preparation: Ali Kashani. All authors reviewed the results and approved the final version of the manuscript.

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