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Research Article

A Novel Methodology for Estimating the Capacity and Level of Service for the New Mega Elliptical Roundabout Intersection

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Mega elliptical roundabout is a new intersection on rural multilane highways. This intersection was developed in a previous paper using simulation data, and the authors found that it is better than interchange (full cloverleaf) in most scenarios of traffic flow. Basically, there are no guidelines or procedures for designing mega elliptical roundabout in AASHTO Green Book, Federal Highway Administration guides, and Highway Capacity Manual. Thus, the purpose of this study is to analyze the traffic operation performance and propose a methodology for calculating the capacity of mega elliptical roundabout and also the level of service by gap acceptance theory. Moreover, this research studied the influence of different values of truck ratios and also different values of a major highway speed on geometric design and traffic operation performance for mega elliptical roundabout. To validate the thoroughness of the proposed methodology, VISSIM simulations were conducted. This research will assist practitioners in determining the appropriate geometric design, assessing mega elliptical roundabout intersections, and making comparisons with other alternatives.

1. Introduction

The designs of conventional intersections cannot often relieve congestion without incurring increased conflicts and also significant improvement costs. Thus, there is a great need for alternative intersections offering the potential to reduce delay, improve safety, and reduce the influence on the environment with fewer effects and a lower cost than traditional solutions [1–4]. Therefore, the authors proposed a new type of intersections which is called "mega elliptical roundabout" in a previous paper [5]. Totally, they analyzed 1134 scenarios by VISSIM software to analyze the initial feasibility and determine the best scenarios of geometric design for mega elliptical roundabout intersections. They compared mega elliptical roundabout with the interchange (full cloverleaf). They found that mega elliptical roundabout as an intersection is better than the interchange (full cloverleaf) in some scenarios of traffic flow, but mega elliptical

roundabout as an interchange is better than the interchange (full cloverleaf) in all scenarios of traffic flow relative to delay time, fuel consumption, and emission.

Based on the previous studies, intersection analysis models generally fall into three categories: simulation models, empirical models, and analytical models. Simulation models are useful in the initial feasibility analysis of new types of intersections which do not have Highway Capacity Manual (HCM) procedures and in comparing them with current intersections [6–14]. Empirical models rely on field data to develop relationships between geometric design features and performance measures such as capacity and delay [15–18]. Analytical models are based on the concept of gap acceptance theory, conflict theory, or probability theory [19–29].

The empirical models are generally better but cannot be used to analyze mega elliptical roundabout at present because mega elliptical roundabout is a new type of

intersections, so no field data are available, while the initial feasibility analysis of mega elliptical roundabout has been introduced in another work by simulation models [5].

There are no guidelines or procedures for the design of mega elliptical roundabout in AASHTO Green Book, Federal Highway Administration (FHWA) guides, and Highway Capacity Manual (HCM). Therefore, this research analyzed the traffic operation performance and used the gap acceptance theory to propose a methodology for calculating the capacity of mega elliptical roundabout and also the level of service, to assist practitioners in determining the appropriate geometric design.

The remainder of this research is organized as follows. Section 2 introduces the literature review. Section 3 shows the basic concept of this study. Section 4 presents the proposed methodology. Section 5 shows the assumptions and built-up models. Section 6 presents the statistical analysis of built-up models. Section 7 demonstrates the case description and methodology validation. Section 8 introduces the sensitivity analysis. Section 9 gives the conclusions of this study and proposes future work.

2. Review of the Previous Studies

Mega elliptical roundabout is a new intersection. Its form is an elongated ellipse combining the best functions of the roundabout and the unconventional median U-turn (UMUT) intersection [5]. Therefore, the first efforts for this work looked at the studies related to estimating the capacity and level of service for roundabout, conventional median U-turn (MUT) intersection, and UMUT intersection to determine the ideal methodology to estimate the capacity and level of service for mega elliptical roundabout intersection.

2.1. Roundabout Intersection. Because vehicles enter the roundabout only when the gap in the circulating traffic is large enough, the capacity of the roundabout depends primarily on the circulating flow and the availability of gaps. Therefore, roundabout capacity is measured in terms of the entry capacity, whether by gap acceptance theory [30–32], empirical models [33–39], simulation models [40–43], conflict theory [44], or others [45–47].

Yap et al. [48] examined the worldwide state-of-the-art in roundabout capacity modeling, covering the three main methodologies on which models are based: fully empirical, gap acceptance, and simulation. They found that due to their limitations, each of these methodologies on its own cannot completely explain the complex behavioural and physical processes involved in roundabout entries; hence, all the models require strong semiempirical or fully empirical bases using data obtained from their countries of origin. Differences in driver behaviour and methodologies thus result in differences in predicted capacities by the various models, and although local calibration allows some transferability, it is often limited by the availability of data or an incomplete understanding of the relationships between model parameters and capacity.

Little research exists from the viewpoint of the weaving section in capacity estimation for the roundabout. Diah et al. [49] introduced a model to predict the weaving section flow at the weaving area of Malaysian conventional roundabout by regression models, while Diah et al. [50] studied the relation between the roundabout performance, geometric design of roundabout, and weaving section flow process using Paramics software. Wang and Yang [51] proposed a method to estimate the capacity of the roundabout by modeling weaving gap acceptance at the weaving sections, but they did not calibrate their method.

In the literature, only one paper by Wu and Brilon [52] treated the whole roundabout intersection as one entity. They believe that the total roundabout capacity can be obtained according to traffic volumes for the movements at the intersection by their method, but they did not calibrate their method by empirical data.

The Highway Capacity Manual [53] only provides a methodology for estimating the capacity of each entry lane and the level of service for the single-lane and multilane roundabout. However, HCM [53] neglected the weaving section when designing the roundabout.

2.2. MUT Intersection. Al-masaeid [54] used empirical and gap acceptance approaches to predict the capacity and the delay of U-turn movement at median openings of four lane-divided arterials. Florida Department of Transportation (FDOT) sponsored a lot of projects to develop a model to estimate delay and travel time for two alternatives: right turn followed by U-turn (RTUT) and direct left turn (DLT) [55–57]. Zhou et al. [58] assessed the operational effects of an RTUT and a DLT. They used field data from eight sites in the Tampa and Clearwater areas of Florida to develop delay and travel-time models. They found that vehicles making a DLT experienced longer delay and travel times than those that made an RTUT.

Zhou et al. [59] introduced the regression model for predicting the average weaving speed in weaving segments at RTUT. Also, they developed a theoretical equation to determine the optimal location of median openings on roadways. Liu et al. [60] analyzed the operational effects of RTUT as an alternative to DLT. They collected the field data from 34 sites in central Florida. They developed a binary logit model to the number of drivers who would like to make an RTUT instead of a DLT under different roadway geometric and traffic conditions.

Zhao et al. [61] proposed a lane-based optimization model for the integrated design of the MUT and formulated a multiobjective mixed-integer nonlinear programming problem to optimize the intersection design types, the layout of the intersection, and the signal timings simultaneously. They conducted a numerical analysis to evaluate the performance of the proposed design under various demand and layout scenarios, but they did not calibrate their method by empirical data. Dash et al. [62] used four different methods to estimate the critical gap of U-turns: modified Raff, maximum likelihood, macroscopic probability equilibrium,

and merging behaviour approach by collecting data at seven median openings in India.

The Highway Capacity Manual [53] provides a methodology for estimating the capacity and level of service for MUT intersection. However, HCM [53] neglected the weaving section when designing the MUT intersection.

2.3. UMUT Intersection.

2.3. UMUT Intersection. Shahi and Choupani [15] conducted traffic operation analysis of the UMUT design by the field data. They developed a regression model to calculate the travel time of the minor street through traffic, travel time of the left-turn traffic, speed of the nonweaving flows, weaving time, and speed of the U-turning vehicles. The developed models have been compared with the RTUT models which have been developed by FDOT [55–57]. They found that FDOT models always overestimate travel times.

3. Basic Concept

3.1. Mega Elliptical Roundabout Characteristics. As shown in Figure 1, the mega elliptical roundabout has two essential features.

The first feature is the central island that is elongated on the major highway for providing enough length for weaving sections. Moreover, the form of this island is an ellipse that has an ellipse element (*b*) for providing a suitable basic ellipse roadway radius in order to be appropriate for heavy vehicles that make a U-turn on basic ellipse roadway.

The second feature is the ellipse roadway, which has three parts: the basic ellipse roadway, weaving sections, and nonweaving sections [5].

3.2. The Operation Analysis of Mega Elliptical Roundabout. The mega elliptical roundabout reroutes both of the through and left-turning traffic coming from a minor highway through right turns in order to merge them with the traffic of a major highway on the weaving sections, followed by U-turn on a basic ellipse roadway. Left-turning traffic for a major highway must also make a U-turn on a basic ellipse roadway then a right turn on a minor highway. The conflict between merging the through traffic for a major highway and the traffic from cross-highway can be treated by putting a "Yield" sign on a minor highway and basic ellipse roadway. It gives the priority for a major highway through traffic, as shown in Figure 1.

3.3. The Weaving Pattern on Mega Elliptical Roundabout. To analyze mega elliptical roundabout intersection, it first needs to be broken down into four parts as shown in Figure 2. Second, it needs to convert the intersection turning movements into the weaving volumes. As shown in Figure 2 the volumes are V_1 to V_{12}.

Two weaving patterns are defined in the HCM [53]. According to HCM [53], in two-sided weaving sections, only the movement from ramp to ramp is considered a weaving movement, where the movement of the major highway does not need any lane change, while the minor highway movement needs more than one lane change.

The vehicle movement weaving pattern on mega elliptical roundabout is like a two-sided weaving section configuration where the right hand on-ramp is followed by the left hand off-ramp or vice versa. As shown in Figure 3, basic ellipse roadway-to-minor-highway vehicles must cross all the lanes in order to execute their desired maneuver, while the major highway vehicles do not need any lane change. Note that the movement in part 1 is like that in part 3. Also, as shown in Figure 4, the minor highway to basic ellipse roadway vehicles must cross all the lanes in order to execute their desired maneuver, while the nonweaving vehicles do not need any lane change. Note that the movement in part 2 is like that in part 4.

There are few studies concerning the operation of two-sided weaving sections. Lertworawanich and Elefteriadou [63–65] proposed a methodology for calculating the capacity for all weaving section types based on linear programing techniques and gap acceptance theory. They compared this methodology with the HCM [66] weaving sections model and field capacity. They found that this methodology provides capacity estimates nearer to the observed capacity values in the field than HCM [66, 67].

Also, in two papers by Zhang and Rakha [68, 69] and a doctoral thesis by Yihua Zhang, analytical models for calculating the capacity of all weaving section types were developed using simulated data collected by INTEGRATION software. They validated the analytical models against field observations gathered in Toronto. They found a high consistency between analytical models and field. Also, they found that the proposed analytical models calculate the capacity for weaving sections within 12% of the simulated data, while HCM [66] procedures exhibit errors within 114%.

However, in this research, we have decided to use the gap acceptance model proposed by HCM [53] with some modifications to suit estimation of the weaving section capacity for mega elliptical roundabout for the following reasons:

(1) As described in Section 2, most researchers estimated roundabout capacity in terms of entry capacity. However, the mega elliptical roundabout differs from a roundabout in traffic operations [5].

(2) Researchers who analyzed the roundabout from the viewpoint of the weaving section did not calibrate their method. Also, the weaving pattern on mega elliptical roundabout is like a two-sided weaving section, while the weaving pattern on the roundabout is like a one-side weaving section.

(3) Researchers who analyzed the MUT and UMUT intersections from the viewpoint of the weaving section did not estimate the weaving section capacity.

(4) HCM [53] neglected the weaving section when designing the roundabout and MUT intersection.

(5) Mega elliptical roundabout is new idea for intersections, so no field data are available at present.
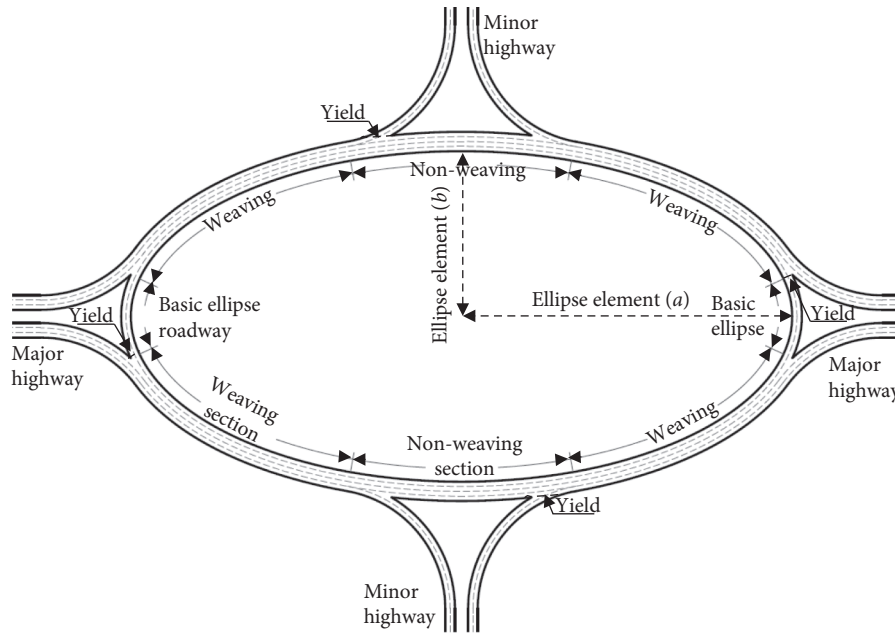
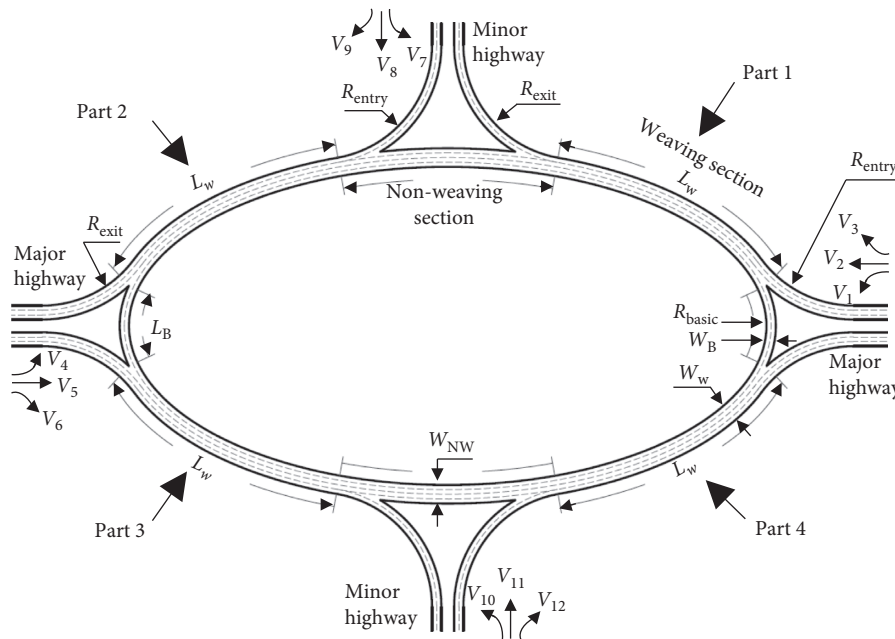FIGURE 1: Geometric elements for mega elliptical roundabout.

FIGURE 2: Flow stream definitions.

(6) HCM is an international reference manual super-vised by an independent committee of experts in this field and therefore is often the basis for policy de-cisions when choosing an intersection.

4. Methodology

This section aims to propose a methodology for calculating the capacity of mega elliptical roundabout in addition to the level of service by gap acceptance theory. The general methodology for analyzing mega elliptical roundabout in-tersection operations is shown in the flowchart in Figure 5. These methodology steps are described in detail as follows:

Step 1: adjust volume.

HCM [53] proposed equation (1) to convert demand volumes to flow rates at equivalent ideal conditions.

$$v_i = \frac{V_i}{(\text{PHF} * f_{\text{HV}})}, \tag{1}$$

FIGURE 3: The weaving pattern for weaving section on mega elliptical roundabout (part 1). $V_{MA.MI}$ = traffic volume in outer lane from major highway to minor highway (veh/h)–V_3; $V_{MA.N}$ = traffic volume from major highway to nonweaving section (veh/h)–$V_2 + V_1$; $V_{B.MI}$ = conflicting volume from basic ellipse roadway to minor highway (veh/h)–$V_{11} + V_4$; $V_{B.N}$ = traffic volume in inner lane from basic ellipse roadway to nonweaving section (veh/h)–V_{10}; V_W = total weaving volume in the weaving section (veh/h)–$V_{B.MI}$; V_{NW} = total nonweaving volume in the weaving section (veh/h)–$V_{MA.MI} + V_{MA.N} + V_{B.N}$.
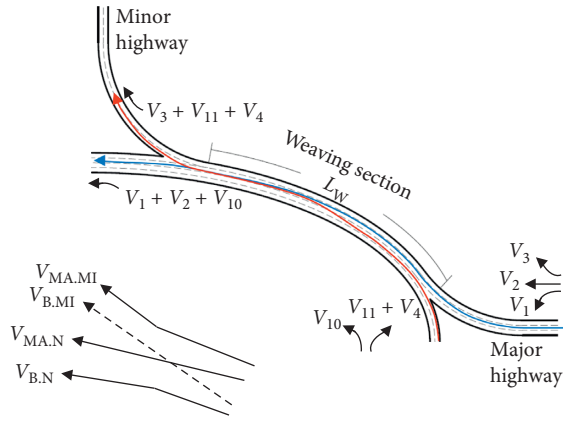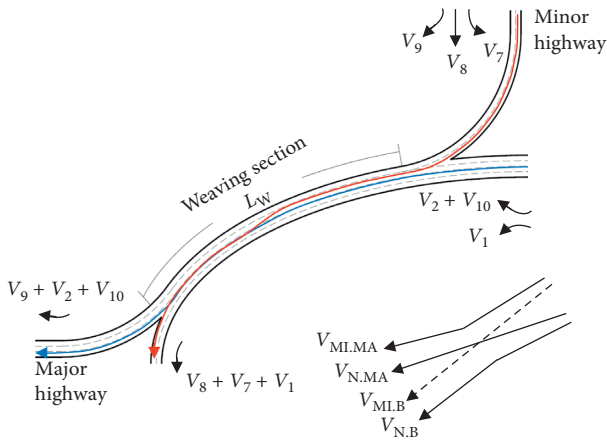

FIGURE 4: The weaving pattern for weaving section on mega elliptical roundabout (part 2). $V_{MI.MA}$ = traffic volume in outer lane from minor highway to major highway (veh/h)–V_9; $V_{MI.B}$ = conflicting traffic volume from minor highway to basic ellipse roadway (veh/h)–$V_8 + V_7$; $V_{N.MA}$ = traffic volume from nonweaving section to major highway (veh/h)–$V_2 + V_{10}$; $V_{N.B}$ = traffic volume in inner lane from nonweaving section to basic ellipse roadway (veh/h)–V_1; V_W = total weaving volume in the weaving section (veh/h)–$V_{MI.B}$; V_{NW} = total nonweaving volume in the weaving section (veh/h)–$V_{MI.MA} + V_{N.MA} + V_{N.B}$.

where v is the peak 15-minute flow rate in an hour (pc/h), V is the hourly volume (veh/h), PHF is the peak-hour factor, and f_{HV} is the heavy vehicle adjustment factor estimated in

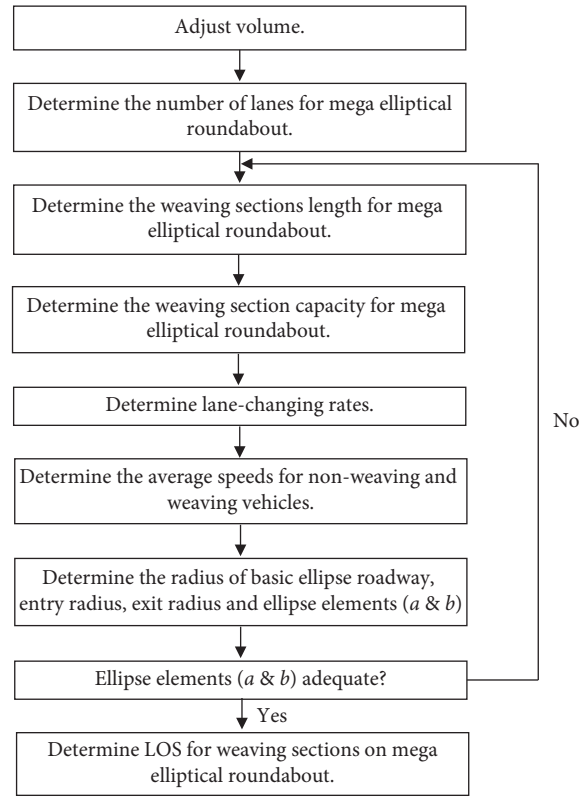$$f_{HV} = \frac{1}{1 + P_T \left(E_T - 1\right)}, \quad (2)$$

FIGURE 5: Methodology flowchart.

where P_T is the proportion of buses and trucks in a traffic stream and E_T is passenger car equivalents for buses and trucks. By following HCM [53], the E_T value is assumed as 1.5, which is the proposed value for intersections in the level area.

Step 2: determine the number of lanes for mega elliptical roundabout.

Mohamed et al. [5] found that the best scenarios of mega elliptical roundabout are the following: when the number of lanes of weaving section (W_W) equals the number of lanes of the nonweaving section (W_{NW}) and also equals the number of lanes of major highway plus one lane.

$W_W = W_{NW}$ = number of lanes of major highway +1

Moreover, the number of lanes of basic ellipse roadway (W_B) equals the number of lanes of minor highway.

W_B = number of lanes of minor highway

where W_W is the number of lanes of weaving section, W_{NW} is the number of lanes of the nonweaving section, and W_B is the number of lanes of basic ellipse roadway, as shown in Figure 2.

Step 3: determine the weaving sections length for mega elliptical roundabout.

HCM [53] defined the weaving section length (short length) as the distance between the end points of any barrier markings that prohibit or discourage lane

changing. Consequently, several geometric design scenarios for mega elliptical roundabout intersection were drawn using AutoCAD software to determine the relationship between the weaving section length (L_W) and ellipse elements (a) and (b), as described in Section 5. The following is a regression equation that can estimate the length of weaving section based upon ellipse elements (a) and (b).

If $b = 0.5a$

$$L_W = 0.868\,a - 7.271. \tag{3}$$

If $b = 0.75a$

$$L_W = 0.721\,a + 12.528, \tag{4}$$

where a is ellipse element (ft), b is ellipse element (ft), and L_W is the weaving section length for mega elliptical roundabout intersection (ft), as shown in Figure 2.

Step 4: determine weaving section capacity.

The HCM [53] proposed equation (5) to estimate the capacity. It is important to mention that the N_{WL} term in the equation of HCM [53] has been deleted because it equals zero for two-sided weaving sections.

$$C = \left[C_H - \left[438.2\,(1 + VR)^{1.6}\right] + (0.0765 * L_W)\right] \\ * W_W * f_{HV}, \tag{5}$$

where C is the capacity for weaving section (veh/h/ln), C_H is the capacity for major highway under ideal conditions and free-flow speed (pc/h/ln), and VR is the weaving ratio. It is the ratio of the weaving flow rate to the total flow rate in weaving section (pc/h) estimated in

$$VR = \frac{v_W}{(v_W + v_{NW})}, \tag{6}$$

where v_W is the total weaving flow rate (pc/h) and v_{NW} is the total nonweaving flow rate in weaving section (pc/h).

Step 5: determine lane-changing rates.

Lane changes fall into three different categories: (1) Lane-changes which must be made by the weaving vehicles to complete a weaving maneuver successfully happen when the weaving vehicles leave weaving section on the lane nearest to their entry point and enter weaving section on the lane nearest to their desired destination. (2) Additional lane changes which may be made by the weaving vehicles happen when weaving vehicles enter weaving section on the lane next to the lane nearest to their desired destination or these vehicles leave on the lane next to the lane nearest to their entry point. These lane changes are based upon

driver choices because these are optional. (3) Lane changes which may be made by nonweaving vehicles in weaving section are generally made for avoiding weaving turbulence. These lane changes are based upon driver choices because these are always optional [67].

As shown in Figure 3, the basic ellipse roadway to minor highway vehicles must make one required lane change, assuming they enter the weaving section on the right lane of basic ellipse roadway. Thus, $LC_{BM} = 1$. As shown in Figure 4, the minor highway to basic ellipse roadway vehicles must also make one required lane change, assuming they enter the weaving section on the left lane of minor highway. Thus, $LC_{MB} = 1$. The following lane-changing values can be computed from equations (7) and (8)

For part 1 or part 3

$$LC_{MIN} = LC_{BM} * v_{B.MI}. \tag{7}$$

For part 2 or part 4

$$LC_{MIN} = LC_{MB} * v_{MI.B}, \tag{8}$$

where LC_{MIN} is the minimum number of the lane changes (lc/h), LC_{BM} is the minimum number of the required lane changes for basic ellipse roadway to minor highway (lc/h), $v_{B.MI}$ is the flow rate of basic ellipse roadway to minor highway (pc/hr), LC_{MB} is the minimum number of the required lane changes for minor highway to basic ellipse roadway, and $v_{MI.B}$ is the flow rate of minor highway to basic ellipse roadway (pc/hr).

The total number of the lane changes made within the weaving section can be predicted by expanding the value of LC_{MIN} to include the number of optional lane changes which are made by both the weaving vehicles and the nonweaving vehicles. The total number of the lane changes which are made by weaving vehicles is calculated as

$$LC_W = LC_{MIN} + 0.39\left[(L_W - 300)^{0.5} W_W^2 (1 + ID)^{0.8}\right], \tag{9}$$

where LC_W is the total number of lane changes made by weaving vehicles (pc/h) and ID is interchange density (int/mi).

The total number of the lane changes which are made by the nonweaving vehicles is calculated as follows.

Firstly, estimate the index

$$INDEX = \frac{(L_W * ID * v_{NW})}{10000}. \tag{10}$$

Then, select the equation from Table 1 based upon the index value.

TABLE 1: The equations for estimating the number of nonweaving lane changes [53].

Index	Equation for LC_{NW}
≤1300	$LC_{NW1} = (0.206 v_{NW}) + (0.542 L_W) - (192.6 W_W)$
>1300 and <1950	$LC_{NW} = W_W + [(LC_{NW2} - LC_{NW1}) * [INDEX - 1300/650]]$
≥1950	$LC_{NW2} = 2135 + 0.233 (v_{NW} - 2000)$

Here, LC_{NW} is the total number of the lane changes which are made by the nonweaving vehicles (pc/h). The value of LC_{NW} must be equal to or greater than zero.

The total number of lane changes occurring in weaving section (LC_{All}) is estimated as

$$LC_{ALL} = LC_W + LC_{NW}. \tag{11}$$

Step 6: determine the average speeds for nonweaving and weaving vehicles.

The average speeds for nonweaving and weaving vehicles are estimated by the following regression-based equations proposed by HCM [53]:

$$
\begin{aligned}
S_W &= 15 + \left[\frac{(FFS - 15)}{(1 + WI)} \right], \\
S_{NW} &= FFS - (0.0072 * LC_{MIN}) - \left(\frac{(0.0048 * v)}{W_W} \right), \\
WI &= 0.226 \left(\frac{LC_{ALL}}{L_W} \right)^{0.789}, \\
S &= \left(\frac{v_W + v_{NW}}{(v_W/s_W) + (v_{NW}/s_{NW})} \right),
\end{aligned}
\tag{12}
$$

where S_W is the average speed of the weaving vehicles (mi/h), FFS is the free-flow speed of the major highway (mi/h), WI is the weaving intensity factor of the weaving speed, S_{NW} is the average speed of the nonweaving vehicles (mi/h), v is the total nonweaving and weaving flow rate (pc/h), and S is the average speed of all the vehicles in weaving sections (mi/h).

Step 7: determine the radius of basic ellipse roadway, entry radius, exit radius, and ellipse elements (a and b). AASHTO [70] proposed equation (13) to estimate the radius of basic ellipse roadway, entry radius, and exit radius.

$$R = \frac{S^2}{15 (f + 0.01e)}, \tag{13}$$

where R is radius of basic ellipse roadway which is equal to the entry radius as well the exit radius (ft), as shown in Figure 2. f is side friction factor, and e is rate of basic ellipse roadway superelevation.

As described in Section 5, the ellipse elements (a) and (b) can be estimated based upon the radius of basic ellipse roadway (R) by the following regression equations.

If $b = 0.5a$

$$a = 3.954 R - 27.427. \tag{14}$$

If $b = 0.75a$

$$a = 1.778 R - 8.846. \tag{15}$$

Step 8: determine LOS for weaving sections on mega elliptical roundabout.

The HCM [53] proposed equation (16) to estimate the density from the average speed.

$$D = \left(\frac{(v/W_W)}{S} \right), \tag{16}$$

where D is average density within the weaving section (pc/mi/ln) and v is the total nonweaving and weaving flow rate (pc/h). From Table 2, we can determine the LOS.

5. Built-Up Models

By using AutoCAD software, several geometric design scenarios for mega elliptical roundabout intersection were drawn. The linear regression analysis was also used to determine the following relationships:

The relationship between the weaving section length (L_W) and the ellipse elements (a) and (b)—equations (3) and (4)

The relationship between the radius of basic ellipse roadway (R_{basic}) and the ellipse elements (a) and (b)—equations (14) and (15)

The relationship between the length of basic ellipse roadway (L_B) and the ellipse elements (a) and (b)—equations (17) and (18)

The mega elliptical roundabout provides appropriate storage lanes for vehicles making a U-turns by providing a sufficient length of basic ellipse roadway. The length of basic ellipse roadway (L_B) can be estimated based upon the ellipse elements (a) and (b) by the following regression equations:

If $b = 0.5a$,

$$L_B = 0.235 a - 29.365. \tag{17}$$

If $b = 0.75a$,

TABLE 2: Level of service for weaving sections on mega elliptical roundabout intersection [53].

Level of service	Density range (pc/mi/ln)
A	0–12
B	>12–24
C	>24–32
D	>32–36
E	>36–40
F	>40

$$L_B = 0.524\,a - 44.016, \qquad (18)$$

where L_B is the length of basic ellipse roadway (ft), as shown in Figure 2.

The regression models were developed using AutoCAD data with the following assumptions and characteristics:

The entry radius of major highway (R_{entry}) equals the entry radius of minor highway, as shown in Figure 2

The entry radius (R_{entry}) equals the radius of basic ellipse roadway (R_{basic}) and also equals the radius of exit (R_{exit}) whether for the minor or major highway, as shown in Figure 2

Lane width equals 12.00 ft

Median width of the major and minor highway equals 32.80 ft

The minimum value for an ellipse element (a) in all scenarios equals 328 ft

The maximum value for an ellipse element (a) in scenarios when ($b = 0.5a$) equals 4920 ft

The maximum value for an ellipse element (a) in scenarios when ($b = 0.75a$) equals 2130 ft

The intersection is four-legged

The intersection is a six-lane-divided highway with a four-lane-divided highway

6. Statistical Analysis of Built-Up Models

The regression models were developed using the data that were compiled by the AutoCAD software, and a linear regression method was accomplished using SPSS software. Regression results of the relationship between the weaving section length (L_W) and ellipse element (a) and also of the relationship between the length of basic ellipse roadway (L_B) and ellipse element (a) when ($b = 0.5a$) and also when ($b = 0.75a$) are shown in Table 3. Moreover, regression results of the relationship between the ellipse element (a) and the radius of basic ellipse roadway (R) when ($b = 0.5a$) and also when ($b = 0.75a$) are shown in Table 4.

R-square value of all linear models is very high (99.9%), which means that 99.9% of the variation independent variables can be explained by these models. Also, for all models, the value of the standard error of the estimate (positive square root of variance of the errors), which typically measures the difference between dependent variables value with the "true" value, is relatively small.

Similar to the standard error of the estimate, the standard error presents the standard error of the coefficient estimates. Essentially, they measure how these coefficients vary from sample to sample. The models are more reliable as the standard error decreases. The t-statistic is the coefficient divided by its standard error. This is based on the following assumption: if the standard errors of the estimate (population errors) are normally distributed, then it can be shown that the sample estimates for coefficients of the model follow a t-distribution [71]. The t-statistic represents the size of the standard error relative to the estimated coefficient; therefore, the model quality improves as the absolute value of t-statistic increases. For those reasons, we can conclude that these models are adequate for predicting the dependent variables.

7. Model Validation and Analysis

7.1. Case Description. To validate the thoroughness of the proposed methodology, VISSIM simulations were conducted. Mega elliptical roundabout intersection which was analyzed was the intersection of the six-lane-divided highway with the four-lane-divided highway, where the intersection was four-legged. The study used hypothetical values of traffic volumes. Traffic volumes of the major highway approaches were varied from 1000 to 2500 veh/h/ approach with 500 veh/h/approach increments (i.e., 4 volume levels). Also, traffic volumes of the minor highway were varied from 500 to 1000 veh/h/approach with 500 veh/h/approach increments (i.e., 2 volume levels). The left-turn volume percentage, the right-turn volume percentage, and the proportion of trucks and buses were considered equal to 20%. The major highway speed was considered 62 mi/h, the peak-hour factor (PHF) equals 0.95, the basic ellipse roadway superelevation equals 2%, and the ellipse element (b) equals 0.75 ellipse element (a). In total, seven scenarios of traffic volume combination for the mega elliptical roundabout design were analyzed, including different levels of the major highway volume and minor highway volume.

7.2. Methodology Validation. To test the accuracy of the proposed methodology, the simulation models for each scenario listed above were built with the VISSIM software package. The parameters were obtained based on the observation of the real two-sided weaving sections in Harbin to ensure its rationality, and the parameters of the VISSIM simulation model must be modified accordingly. Seven simulations of different random seeds were conducted, and the final results were the average values over seven simulations. The results of the estimation models and simulations for density and average speed are given in Table 5 when the traffic volume for the minor highway equals 500 veh/h. Moreover, these results are given in Table 6 when the traffic volume for the minor highway equals 1000 veh/h.

For all traffic volume cases on the major highway and minor highway, there was no significant difference in methodology results and simulation for estimating average

TABLE 3: Regression results of the relationship between L_W, L_B, a, and b.

Equation number	Dependent variables		Independent variables		Std. error of the estimate	R^2
			Constant	a (ft)		
If $b = 0.5a$						
3	L_W	Coefficients	−7.271	0.868	5.027	1.00
		Standard error	2.658	0.001		
		t-statistics	−2.735	849.058		
20	L_B	Coefficients	−29.365	0.235	9.869	0.999
		Standard error	5.219	0.002		
		t-statistics	−5.627	117.287		
If $b = 0.75a$						
4	L_W	Coefficients	12.528	0.721	3.321	1.00
		Standard error	2.357	0.002		
		t-statistics	5.315	382.886		
21	L_B	Coefficients	−44.016	0.524	6.673	1.00
		Standard error	4.736	0.004		
		t-statistics	−9.294	138.455		

TABLE 4: Regression results of the relationship between a, R, and b.

Equation number	Dependent variables		Independent variables		Std. error of the Estimate	R^2
			Constant	R (ft)		
If $b = 0.5a$						
17	a	Coefficients	−27.427	3.954	6.968	1.00
		Standard error	3.715	0.006		
		t-statistics	−7.383	705.367		
If $b = 0.75a$						
18	a	Coefficients	−8.846	1.778	1.580	1.00
		Standard error	1.128	0.002		
		t-statistics	−7.84	1115.688		

TABLE 5: Results of methodology, simulations, and relative error when the traffic volume for the minor highway equals 500 veh/h.

Traffic volume for the major highway		Part 1 or part 3			Part 2 or part 4		
		Average speed (mi/h)	Density (pc/mi/ln)	LOS	Average speed (mi/h)	Density (pc/mi/ln)	LOS
1000	VISSIM	52.85	7.6	A	52.7	6.7	A
	Methodology	55.2	8.4	A	56.2	7.2	A
	Relative error	4.4%	10.5%		6.6%	7.4%	
1500	VISSIM	51.9	10.7	A	51.88	8.7	A
	Methodology	53.9	11.8	A	55.8	9.3	A
	Relative error	3.8%	10.28%		7.5%	6.9%	
2000	VISSIM	49.5	14.2	B	50.2	11.03	A
	Methodology	52.4	15.5	B	55.4	11.5	A
	Relative error	5.8%	9.1%		10.3%	4.2%	
2500	VISSIM	43.7	19.6	B	45.9	14.2	B
	Methodology	51	19.3	B	54.9	13.7	B
	Relative error	16.7%	−1.5%		19.6%	−3.5%	

speed as well as density. The relative error range was [1.5%, 19.6%] for the average speed, while the relative error range was [−3.5%, 13.4%] for the density. The main cause of the existing relative error was the random VISSIM simulation results which led to some deviations from the average speed and density in the estimated models.

8. Sensitivity Analysis

8.1. Impact of Trucks Proportion on the Value of Ellipse Element (a), Density, and Average Speed. To study the influence of different ratios of trucks on geometric design and traffic operation performance for mega elliptical roundabout, the

TABLE 6: Results of methodology, simulations, and relative error when the traffic volume for the minor highway equals 1000 veh/h.

Traffic volume for the major highway		Part 1 or part 3			Part 2 or part 4		
		Average speed (mi/h)	Density (pc/mi/ln)	LOS	Average speed (mi/h)	Density (pc/mi/ln)	LOS
1000	VISSIM	52	9.7	A	49.6	10.2	A
	Methodology	52.8	11	A	52.8	11	A
	Relative error	1.5%	13.4%		6.4%	7.8%	
1500	VISSIM	49.8	13.2	B	44.9	13.57	B
	Methodology	51.4	14.6	B	52.3	13.3	B
	Relative error	3.2%	10.6%		16.4%	−1.9%	
2000	VISSIM	46.6	16.75	B	44.3	16.2	B
	Methodology	50	18.5	B	51.8	15.7	B
	Relative error	7.3%	10.4%		16.9%	−3%	

proposed methodology was used to predict the value of an ellipse element (a), density, and average speed at different ratios of trucks. The used scenarios are the same scenarios described in Section 7.1, but with different values of truck ratios which are 2, 5, 10, 15, and 20%.

The relationships between major highway traffic volume and the value of an ellipse element (a), density, and average speed for vehicles on the weaving sections for mega elliptical roundabout at different ratios of trucks when minor highway traffic volume equals 500 veh/h and 1000 veh/h are presented in Figures 6 and 7, respectively. The figures show that the average speed for vehicles decreases with the increase in truck ratios, but the differences are not significant. The decrease in average speed may be because of traffic interaction that occurs due to increasing the truck proportion, while the fact that the differences are not significant may be because mega elliptical roundabout is not conventional intersection. It gives priority to the vehicles entering from the major highway. Therefore, the movement on the weaving sections of mega elliptical roundabout intersection is like the movement on the two-sided weaving sections of any highway.

Moreover, the density increases with the increase in truck ratios, but the differences are not significant. This is most likely because the average speed decreases with the increase in truck ratios, thereby increasing the density, as described in equation (16).

In addition, the value of an ellipse element (a) decreases with the increase in truck ratios, but the differences are not significant. This is most likely because the average speed decreases with the increase in truck ratios that can lead to decreasing the value of radius of basic ellipse roadway, as described in equation (13), thereby decreasing the ellipse element (a), as described in equations (14) and (15).

Based on the above analysis, the influence of the different ratios of trucks on geometric design and traffic operation performance for mega elliptical roundabout is not significant.

8.2. Impact of Major Highway Speed on the Value of Ellipse Element (a), Density, and Average Speed. To study the influence of different values of a major highway speed on geometric design and traffic operation performance for mega elliptical roundabout, the proposed methodology was used to predict the value of an ellipse element (a), density, and average speed at different values of a major highway

speed. The used scenarios are the same scenarios described in Section 7.1, but with different values of a major highway speed which were 30, 40, 45, 50, and 62 mi/h.

The relationships between major highway traffic volume and the value of an ellipse element (a), density, and average speed for vehicles on the weaving sections for mega elliptical roundabout at different values of a major highway speed when minor highway traffic volume is equal to 500 veh/h and 1000 veh/h are presented in Figures 8 and 9, respectively. The figures show that the average speed for vehicles increases with the increase in major highway speed, but the density decreases. This is probably because mega elliptical roundabout gives priority to the vehicles entering from the major highway. Therefore, the movement on the weaving sections of mega elliptical roundabout is like the movement on the two-sided weaving sections of any highway.

Also, the value of an ellipse element (a) increases with the increase in major highway speed because the average speed for vehicles increases, which can lead to increasing the value of radius of basic ellipse roadway, thereby increasing the ellipse element (a), as described in equations (13)–(15). Moreover, the value of an ellipse element (a) has doubled when the major highway speed increased from 30 mi/h to 40 mi/h, 40 mi/h to 50 mi/h, and 50 mi/hr to 62 mi/h. This is probably because mega elliptical roundabout island has an ellipse element (b) for providing a suitable radius for basic ellipse roadway in order to be appropriate for heavy vehicles that make a U-turn on basic ellipse roadway. This radius is calculated based on the average speed for vehicles on weaving sections from equation (13).

Furthermore, the average speed on part 2 or part 4 is greater than the average speed on part 1 or part 3 for mega elliptical roundabout in all scenarios. This is probably because total weaving volume on part 2 or part 4 is lower than total weaving volume on part 1 or part 3, as shown in Figures 3 and 4, thereby increasing the average speed. For the same reason, the value of an ellipse element (a) is always calculated according to the average speed on part 2 or part 4 from equations (14) and (15)

By analyzing Figure 8, it is possible to confirm the following.

In the case of the value of major highway speed equal to 30 mi/hr, minor highway volume = 500 veh/h, ellipse element (a) = 410 ft, and major highway volume ≤ 1500 veh/h, density is lower than 32 pc/mi/ln (level of service A-B-C).
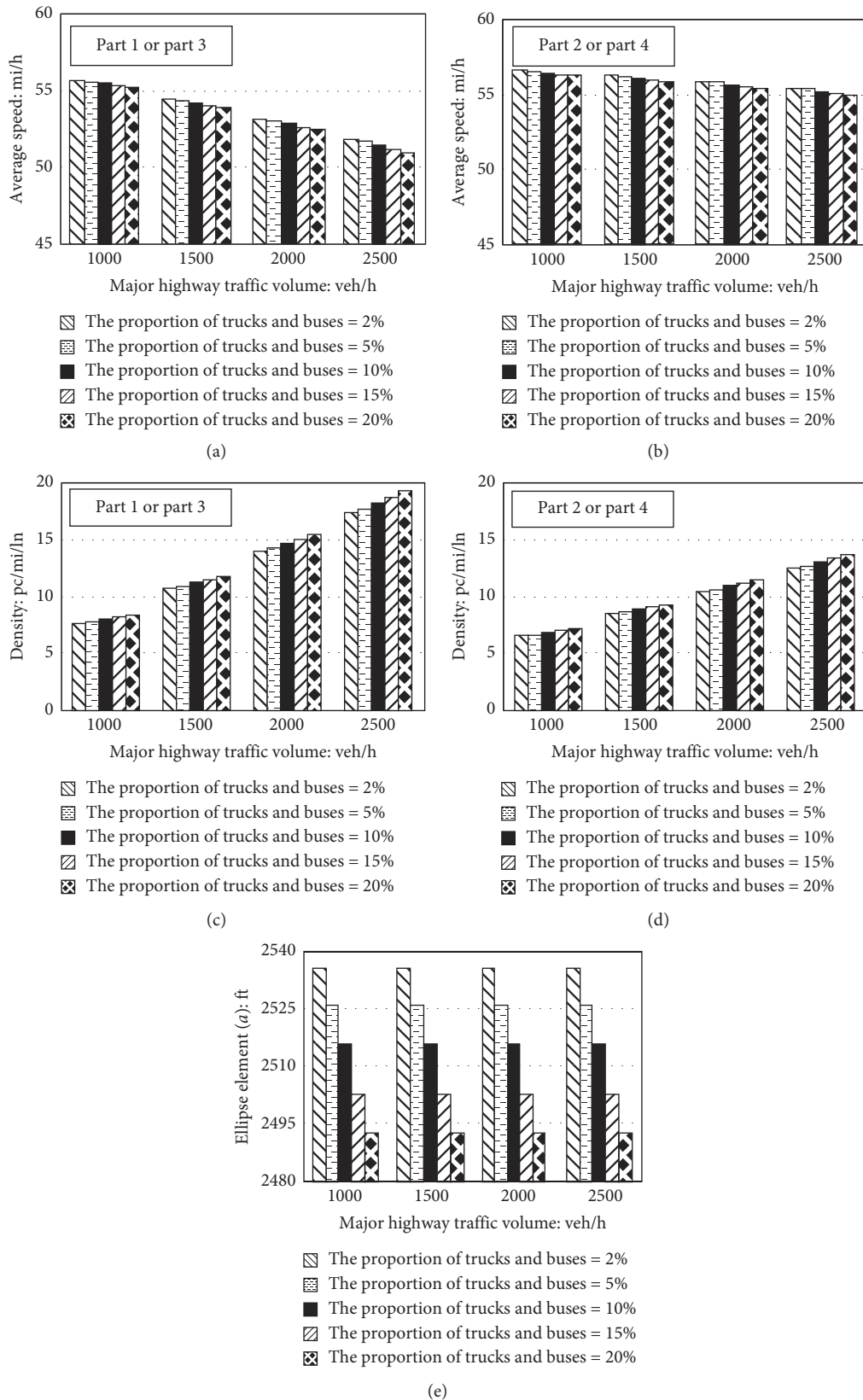
Figure 6: Relationships between major highway traffic volume and the value of an ellipse element (a), density, and average speed at different ratios of trucks when the minor highway traffic volume = 500 veh/h. (a) Average speed for part 1 or part 3, (b) average speed for part 2 or part 4, (c) density for part 1 or part 3, (d) density for part 2 or part 4, (e) ellipse element (a) for mega roundabout.
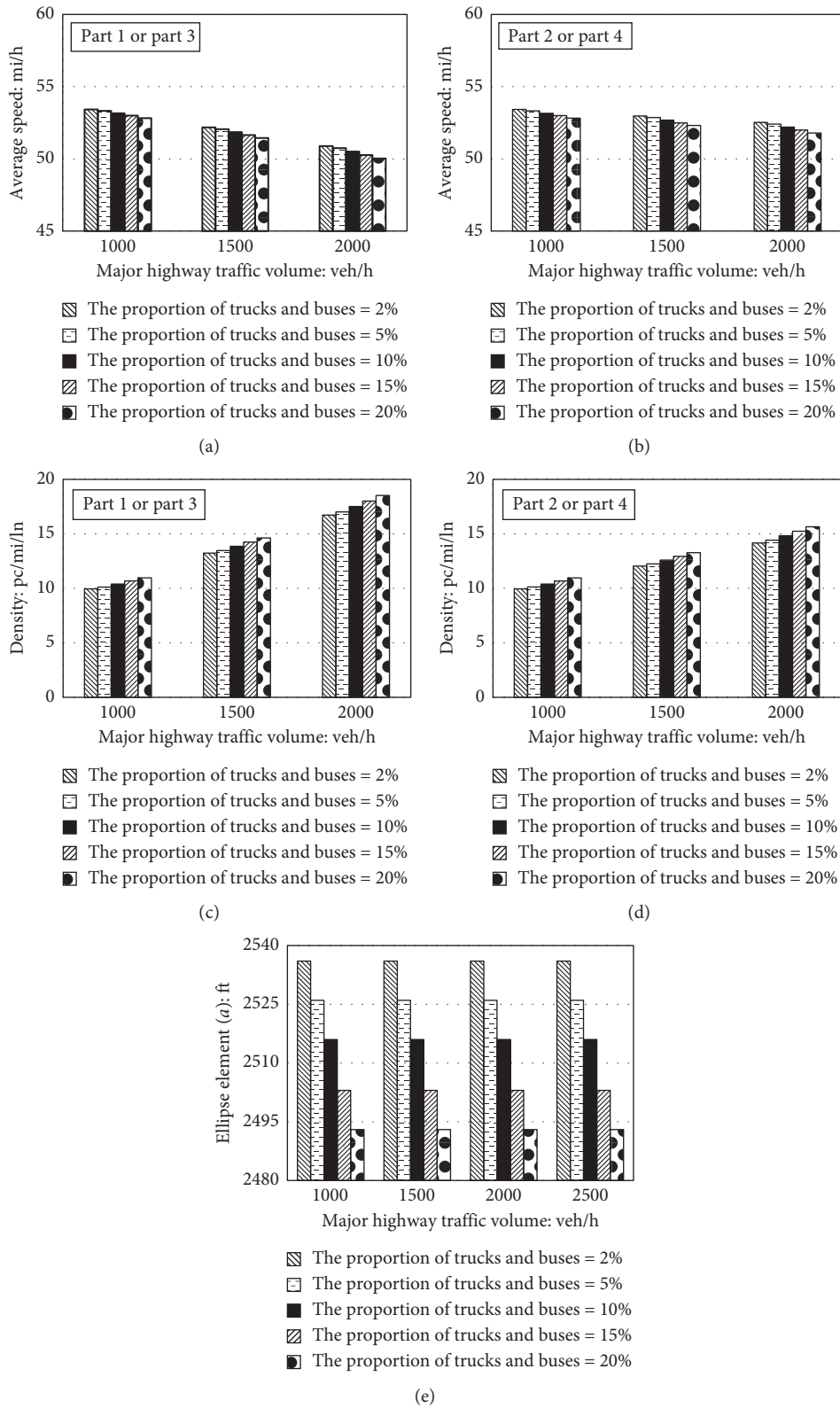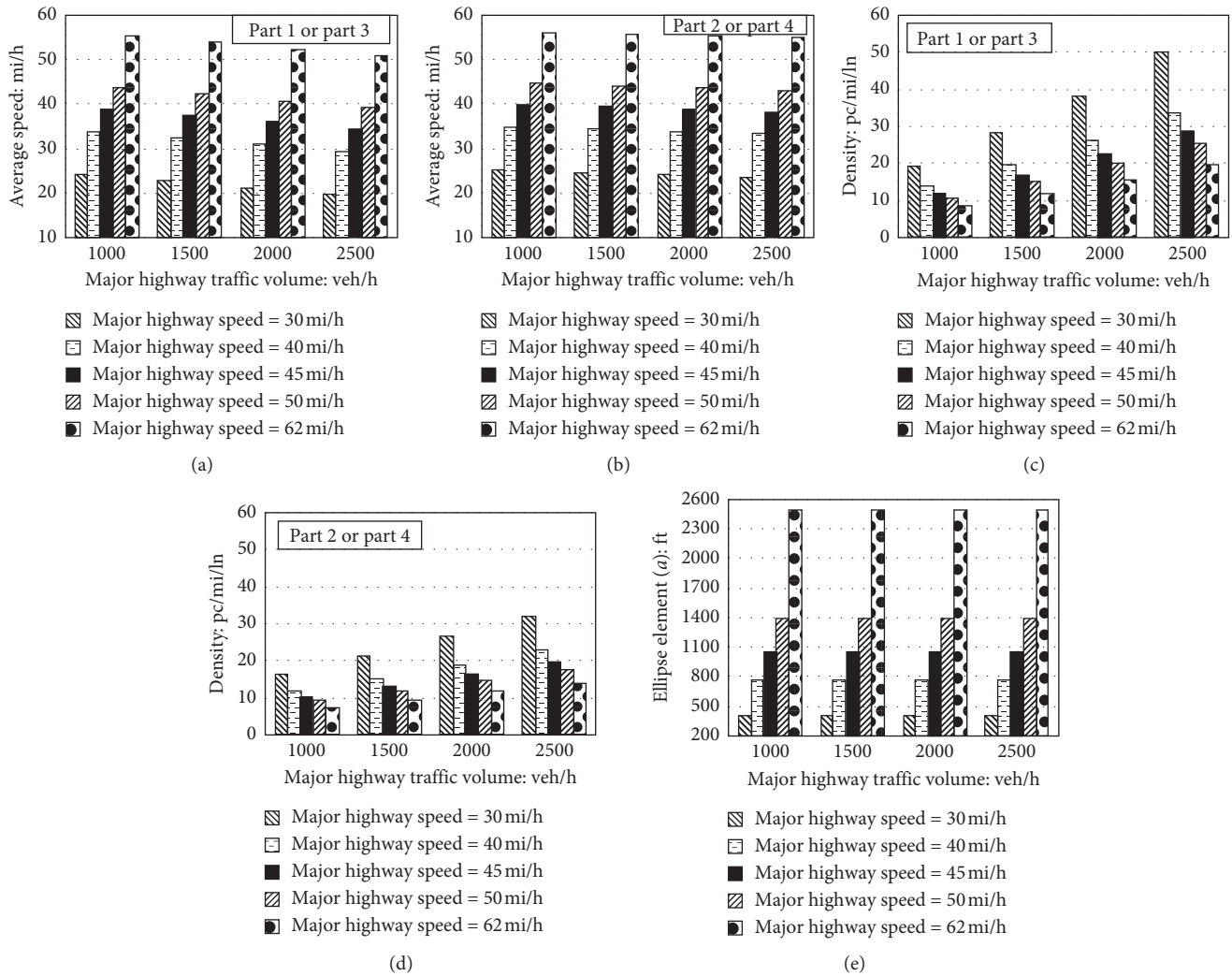
(a)

(b)

(c)

(d)

(e)

FIGURE 7: Relationships between major highway traffic volume and the value of an ellipse element (a), density, and average speed at different ratios of trucks when the minor highway traffic volume = 1000 veh/h. (a) Average speed for part 1 or part 3, (b) average speed for part 2 or part 4, (c) density for part 1 or part 3, (d) density for part 2 or part 4, (e) ellipse element (a) for mega roundabout.

Figure 8: Relationships between major highway traffic volume and the value of an ellipse element (a), density, and average speed at different values of a major highway speed when minor highway traffic volume = 500 veh/h. (a) Average speed for part 1 or part 3, (b) average speed for part 2 or part 4, (c) density for part 1 or part 3, (d) density for part 2 or part 4, (e) ellipse element (a) for mega roundabout.

Also, in the case of the value of major highway speed equal to 40 mi/hr, minor highway volume = 500 veh/h, ellipse element (a) = 771 ft, and major highway volume ≤ 2000 veh/h, density is lower than 32 pc/mi/ln (level of service A-B-C).

By analyzing Figure 9, it is possible to confirm the following.

In the case of the value of major highway speed equal to 30 mi/hr, minor highway volume = 1000 veh/h, ellipse element (a) = 410 ft, and major highway volume ≤ 1000 veh/h, density is lower than 32 pc/mi/ln (level of service A-B-C). Also, in the case of the value of major highway speed equal to 40 mi/hr, minor highway volume = 1000 veh/h, ellipse element (a) = 771 ft, and major highway volume ≤ 1500 veh/h, density is lower than 32 pc/mi/ln (level of service A-B-C).

Based on the above analysis, in highways that have a speed equal to 30 mi/hr, the suitable design of mega elliptical roundabout is ellipse element (a) = 410 ft and ellipse element (b) = 308 ft. This is suitable in the following cases: the values

of a major highway volume ≤ 1500 veh/h and minor highway volume ≤ 500 veh/h; or the values of a major highway volume ≤ 1000 veh/h and minor highway volume ≤ 1000 veh/h. Also, in highways that have a speed equal to 40 mi/hr, the suitable design of mega elliptical roundabout is ellipse element (a) = 771 ft and ellipse element (b) = 578 ft. This is suitable the following cases: the values of a major highway volume ≤ 2000 veh/h and minor highway volume = 500 veh/h; or the values of a major highway volume ≤ 1500 veh/h and minor highway volume = 1000 veh/h. Moreover, in highways that have a speed equal to 45, 50 and 62 mi/hr, the suitable design of mega elliptical roundabout is ellipse element (b) = 0.75 ellipse element (a), and ellipse element (a) = 1053, 1398, and 2493 ft, respectively. This is suitable in the following cases: the values of a major highway volume ≤ 2500 veh/h and minor highway volume ≤ 500 veh/h; or the values of a major highway volume ≤ 2000 veh/h and minor highway volume ≤ 1000 veh/h.
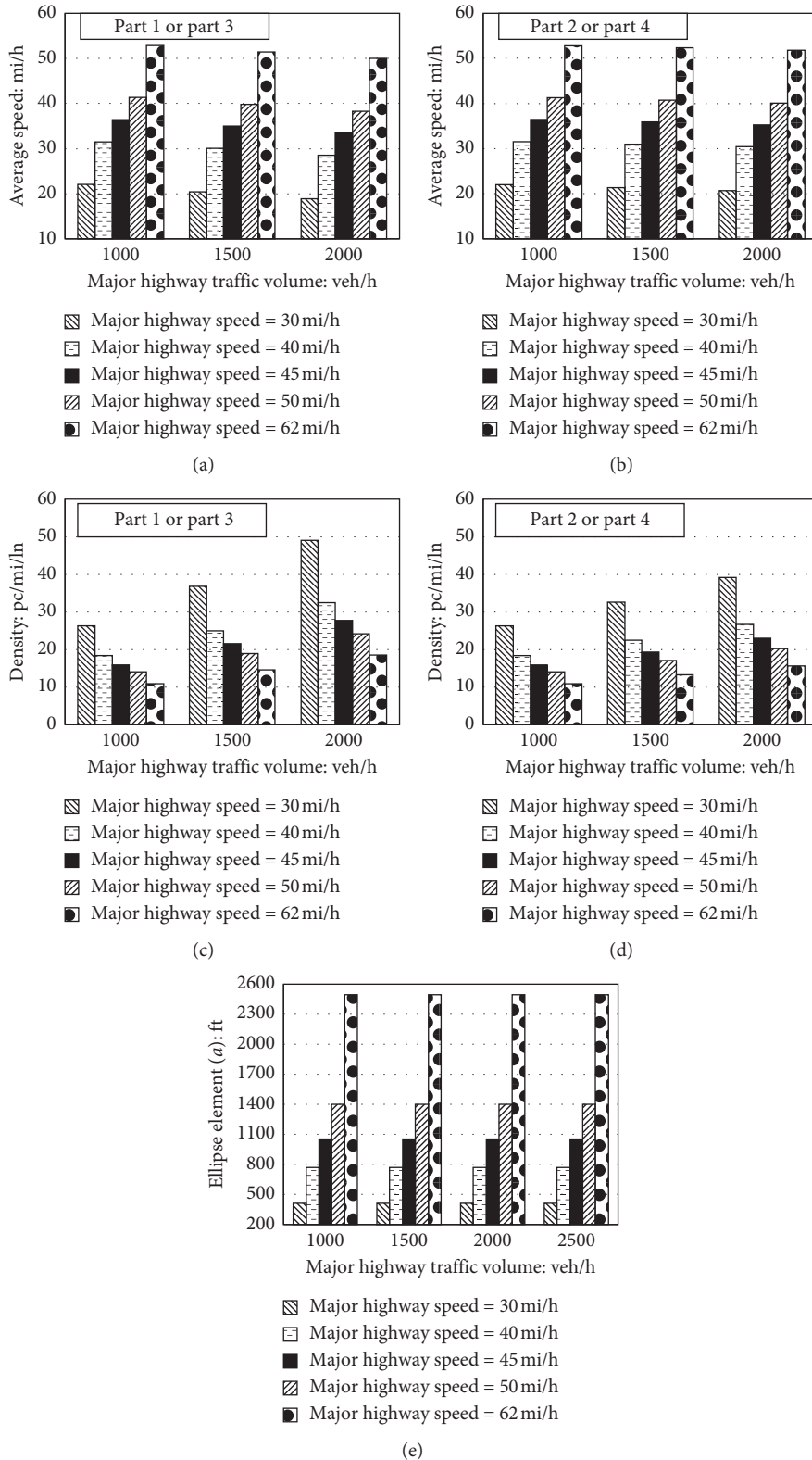
(a)

(b)

(c)

(d)

(e)

Figure 9: Relationships between major highway traffic volume and the value of an ellipse element (*a*), density, and average speed at different values of a major highway speed when minor highway traffic volume = 1000 veh/h. (a) Average speed for part 1 or part 3, (b) average speed for part 2 or part 4, (c) density for part 1 or part 3, (d) density for part 2 or part 4, (e) ellipse element (*a*) for mega roundabout.

9. Conclusions

In this paper, the performance of traffic operations was analyzed for mega elliptical roundabout intersection. Moreover, this paper proposed a methodology for estimating the capacity and level of service for mega elliptical roundabout intersections by gap acceptance theory. Furthermore, explicit VISSIM simulations were performed after calibrating them with field data from real two-sided weaving sections in Harbin to verify the accuracy of the proposed methodology. In addition, regression analysis was implemented by SPSS software to obtain the relationships of ellipse elements with the radius of basic ellipse roadway, the length of basic ellipse roadway, and the length of weaving section. Regression models were developed using the data that were compiled by the AutoCAD software for several geometric design scenarios for mega elliptical roundabout intersection. Also, the influence of different values of truck ratios and also different values of a major highway speed on geometric design and traffic operation performance for mega elliptical roundabout was studied. Based on the regression analysis, methodology validation, and sensitivity analysis, the following can be concluded:

(1) In mega elliptical roundabout intersection, the weaving sections are the key to the efficiency of the intersection as a whole

(2) The models built up in this study are adequate to predict the dependent variables

(3) Estimation methodology of the average speed and the density on the weaving sections of mega elliptical roundabout was confirmed to have a reasonable accuracy

(4) The influence of the different ratios of trucks on geometric design and traffic operation performance for mega elliptical roundabout is not significant, while the influence of the different ratios of a major highway speed is significant

In conclusion, it is clear that this study analyzed the performance of traffic operations and suggested a method for designing mega elliptical roundabout intersections to assist practitioners in determining the appropriate geometric design. Based on the previous studies, the traffic operation and safety are the main measures for assessing the intersections [72–76]. Therefore, further research will be needed to assess the safety performance of mega elliptical roundabout. We plan to use a surrogate safety assessment model developed by FHWA to compare safety aspects of the proposed intersection with those of other alternative intersections.

Data Availability

The basic data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Authors' Contributions

Ahmed I. Z. Mohamed and Yusheng Ci collected the data and analyzed and interpreted the results. Ahmed I. Z. Mohamed and Yiqiu Tan prepared the manuscript draft. All authors contributed to study conception and design, reviewed the results, and approved the final version of the manuscript.

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