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Enhancement of Traffic Performance for Signalized Roundabout Intersections

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Abstract

Signalized roundabouts are used to manage high traffic demand, but they may still experience congestion, queues, and high delay due to unbalanced traffic volumes, turning movements, circulating flow interaction, weaving movements, signal timing, and geometry. This paper evaluates the operational performance of four signalized roundabouts in 10th of Ramadan City: Al-Kafrawy, Al-Rwad, El-Nasagon El-Sharqion, and El-Safera Aziza. It also examines the applicability of the HCM signalized intersection delay procedure by comparing HCM delay estimates with field delay measurements and calibrated VISSIM outputs. Field videos were analyzed to extract traffic volumes, turning movements, vehicle classifications, and delay values. VISSIM models were developed, calibrated, and validated using field delay data, while the agreement among field, VISSIM, and HCM results was assessed using descriptive measures, correlation analysis, and regression modeling. Two enhancement scenarios were also tested: signal timing optimization and conversion to a conventional signalized intersection. The results showed that calibrated VISSIM closely represented field delay, with a mean delay of 52.92 s/veh compared with 50.61 s/veh in the field, while HCM produced a higher mean delay of 67.39 s/veh. Regression analysis showed stronger agreement for field–VISSIM delay ($R^2 = 0.9937$) than field–HCM delay ($R^2 = 0.9303$). The enhancement results indicated that conversion to a conventional signalized intersection achieved greater delay reduction than signal timing optimization, especially where through movement was dominant.

Keywords: Signalized roundabouts; VISSIM simulation; Field delay measurements; Traffic congestion; Delay Time; LOS.

1.Introduction and Literature Review

Population and vehicle growth have increased congestion, crashes, and environmental impacts. Signalized roundabouts, used in high-demand areas, combine roundabout circulation with traffic signals to improve traffic control, reduce delays, and enhance safety [1]. Driver behavior also supports the use of signalized roundabouts. In many developing countries, poor familiarity with roundabout rules causes violations, while signal control improves compliance, safety, and capacity [2]. Signalized roundabouts improve safety and efficiency by balancing traffic flow. When volumes are uneven, signals regulate movement, reduce entry conflicts, and enhance intersection performance [3].

Research on signalized roundabouts mainly covers three areas: simulation-based comparisons with conventional roundabouts, metering strategies for unbalanced demand, and signal timing optimization to improve flow and reduce congestion [4]. Akçelik used SIDRA to compare roundabouts with and without metering signals. The study found that part-time metering reduces queues and delays under uneven demand by controlling selected entries, offering a cost-effective alternative to full signalization [5, 6]. Dryland and Chong found that selective signalization improved flow and safety at a high-demand New Zealand roundabout. Short signal cycles, proper geometry, clear markings, and signage were essential to reduce queuing and support safe operation [7]. Chard's New Zealand case studies highlighted that effective signalized roundabouts require coordinated signal timing, geometry, markings, and safety measures to accommodate different users while maintaining efficient operation [8].

Recent studies show that adaptive signal control and queue detectors can greatly improve signalized roundabouts under congestion. A microsimulation study in Amman reported major reductions in delays and queues using optimized real-time control [9]. Simulation tools like PTV VISSIM are widely used to optimize roundabout signal control. Studies show that appropriate signal timing can reduce delays, improve capacity, and support context-specific traffic management [10]. Studies using SIDRA show that metered roundabouts perform well under unbalanced demand by regulating entry flow, creating gaps for congested approaches, and reducing delays, fuel use, and travel time [11].

Field delay reflects the actual time loss experienced by vehicles under real traffic conditions and is typically measured using observational and tracking methods. Techniques such as video recording with trajectory extraction offer detailed, high-accuracy data on vehicle movements, including speed, acceleration, and lane changes. However, these methods are resource-intensive and require significant processing effort [12, 13]. The floating car, or test vehicle, method estimates travel time and delay by operating a probe vehicle within the traffic stream. While it is straightforward and economical, its accuracy is constrained by limited sample sizes and potential driver-related bias [14, 15]. GPS-based tracking relies on data from mobile devices to enable continuous, large-scale monitoring of traffic conditions, making it well suited for network-level analysis. However, its accuracy may be affected by positioning errors and signal noise, particularly in dense urban areas [16]. Manual observation involves recording delays directly using basic tools such as stopwatches and tally sheets. While it is simple and low-cost, it is susceptible to human error and provides limited data in terms of accuracy and volume [17]. Microscopic traffic simulation is a key tool for assessing transportation system performance, particularly in estimating delays at intersections and across urban networks. Among these, PTV VISSIM is widely adopted for its ability to replicate individual vehicle behavior, such as car-following and lane-changing, enabling detailed evaluation of various delay components [18, 19]. In PTV VISSIM, delay is defined as the excess travel time experienced by a vehicle relative to ideal free-flow conditions. It is computed as the difference between the simulated travel time and the corresponding theoretical travel time based on the desired speed [20]. Analytical delay estimation uses mathematical models based on traffic volume, lane layout, signal timing, and saturation level. The HCM method calculates delay using uniform, incremental, and initial queue delay components, and was used in this study to compare delay at signalized roundabouts.[17].

VISSIM is a behavior-based, time-step simulation model composed of three core elements: traffic control, traffic flow, and data analysis. It is widely used to evaluate infrastructure design and operations, including highway performance, dynamic traffic assignment, multimodal interactions, signal control and optimization, traffic management strategies, and pedestrian movement [21]. Traffic simulation plays an important role in analyzing and assessing various traffic models, offering a cost-effective alternative to real-world testing since no physical system implementation is required [22]. In microscopic simulations, driver behavior is a key component, typically represented through parameters with predefined ranges that can be adjusted according to local traffic conditions. However, because driving patterns vary significantly across regions and environments, default parameter values often fail to accurately reflect the specific characteristics of local traffic conditions [23]. VISSIM incorporates eight vehicle behavior models, including car-following, lane-changing, lateral movement, signal control, autonomous driving, driver error, and mesoscopic representation [24]. The car-following mechanism is based on Wiedemann's psychophysical approach, which describes driver behavior across four states: free driving, approaching, following, and braking, each governed by specific threshold conditions that trigger behavioral changes. Lane-changing behavior is modeled using the Sparmann framework, a rule-based approach that distinguishes between movements toward faster or slower lanes [25]. Traffic simulation accuracy depends on how well vehicle movements are represented. In VISSIM, traffic is modeled as a stochastic, time-step-based system, where individual vehicles follow psychophysical car-following behavior and rule-based lane-changing logic [26]. In VISSIM, time-dependent factors include changes in traffic flow, speeds, driving behavior, lane choice, signal timing, and queue lengths. Accurately modeling these variables is essential for realistic simulation, calibration, and validation [27, 28].

Calibration and validation ensure that traffic simulation models accurately represent field conditions. Calibration adjusts model parameters to match observed data, while validation confirms model accuracy using measures such as delay, queue length, travel time, LOS, and capacity. Relying on multiple measures is necessary, as matching traffic volume alone may not accurately reflect delays or queues [13]. For signalized roundabouts, calibration is especially important due to interactions between demand, geometry, lane behavior, priority rules, signal timing, detector placement, and queue discharge. Therefore, studies commonly use measures such as vehicle delay, stopped delay, queue length, and maximum queue length to evaluate model performance [9].

Despite extensive research on roundabouts, signalized intersections, and traffic simulation, limited studies have examined signalized roundabouts under high-demand urban conditions. Their operation involves complex interactions between circulating flow, entry behavior, weaving, lane changing, geometry, and signal control, which may not be fully captured by conventional delay methods such as the HCM signalized intersection procedure. In addition, simulation accuracy depends on proper calibration and validation using field data and multiple performance measures, rather than default parameters or traffic volume alone. This study addresses these gaps by collecting field data from selected signalized roundabouts in 10th of Ramadan City, developing calibrated VISSIM models, and comparing field delays with VISSIM outputs and HCM estimates.

2.Study Methodology

The study methodology, shown in Figure 1, included office and field work. Office work covered problem definition, intersection selection, data preparation, and base-case VISSIM model development. Field work involved collecting geometric, control, and traffic video data for field delay extraction and HCM estimation. The VISSIM model was calibrated and validated before extracting simulated delay results. These results were compared with field and HCM delays to evaluate performance, identify critical conditions, test VISSIM-based improvement scenarios, and develop conclusions and recommendations.

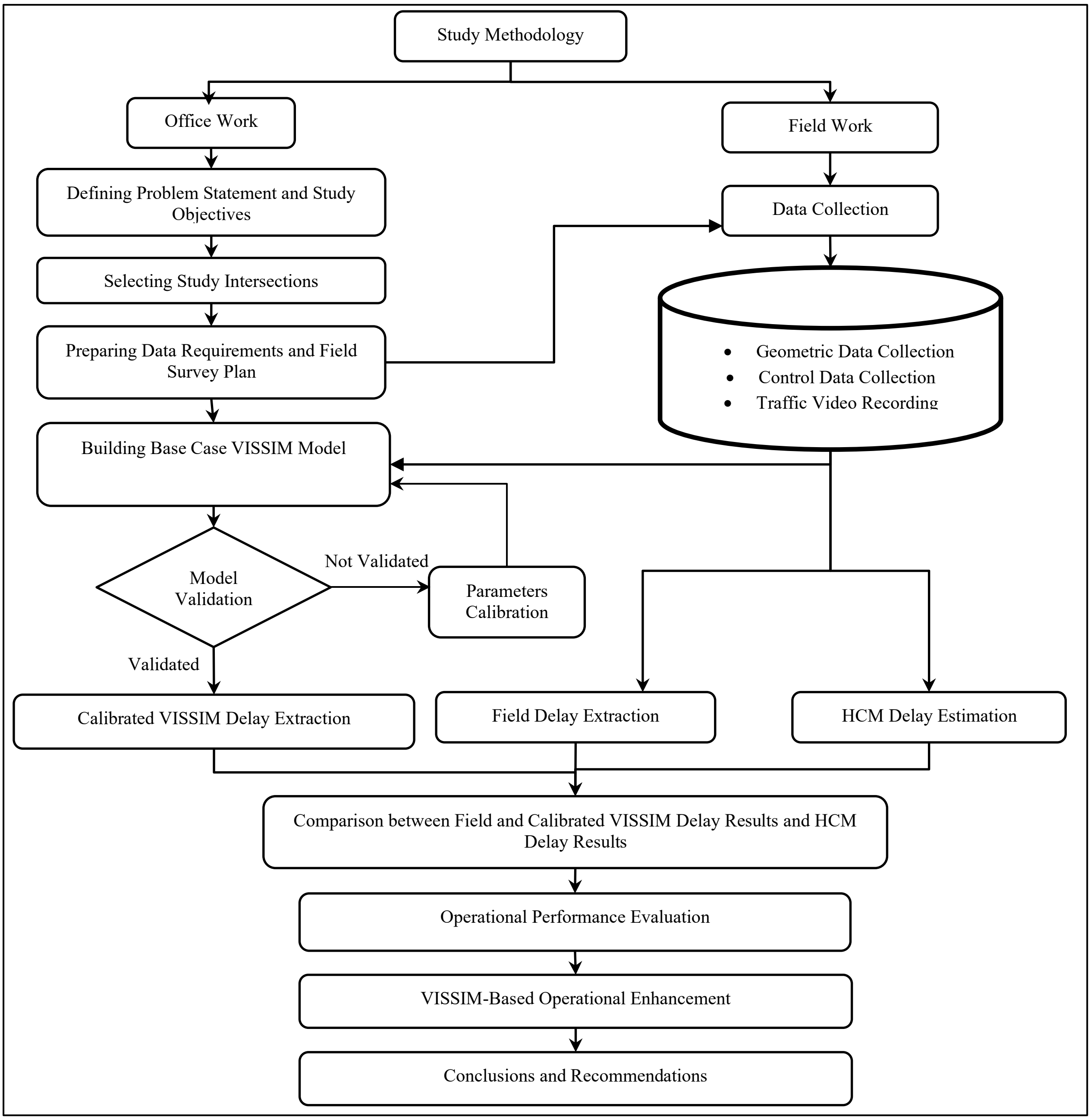


Figure 1. Study methodology flowchart

2.1. Study Area

The study focused on four signalized roundabouts in 10th of Ramadan City: Al-Kafrawy, Al-Rwad, El-Nasagon El-Sharqion, and El-Safera Aziza, as shown in Figure 2. These intersections were selected because they represent major urban roundabouts with high traffic demand, congestion, unbalanced movements, and queue formation during peak periods. Each roundabout consists of four approaches, while their geometric characteristics, including roundabout diameter, central island size, number of circulating lanes, and lane width, vary from one location to another. This variation allowed the study to compare operational performance under different traffic and geometric conditions. For consistency, the approaches were numbered from 1 to 4 and used throughout the analysis to present geometric data, traffic volumes, field delays, VISSIM outputs, and HCM results.

Figure 2 : Locations of the Selected Signalized Roundabouts in 10th of Ramadan City

2.2. Field Survey Preparation

Before the field survey, the required data were organized into three main groups: geometric, signal control, and traffic data. Geometric data described the physical layout of each roundabout, including diameters, lane widths, approach and circulating lanes, and entry–exit configurations. Signal control data included cycle length, phase sequence, and green, yellow, and red times, which were needed to represent the existing control system. Traffic data included volumes, vehicle classifications, turning movements, and field delay measurements to describe demand patterns and observed performance.

A survey plan was prepared to ensure clear coverage of all approaches, circulating movements, entry and exit areas, and queue formation. Video recording was used as the main collection method because it provided a clear view of the actual traffic conditions and allowed repeated review of vehicle movements, as shown in Figure 3. The recorded videos were later used to extract traffic volumes, vehicle classifications, turning movement distributions, and field delay values. The survey covered both peak and off-peak periods to capture variations in traffic demand and operational performance.

Figure 3. Sample Frame from the Traffic Video Recording Used for Data Extraction

2.3.Data Collection

Table 1 summarizes the geometric characteristics of the selected signalized roundabouts, including approach direction, number and width of entry lanes, roundabout and central island diameters, number of circulating lanes, and circulating lane width. These data describe the existing layouts and provide the required geometric inputs for the VISSIM models.

Table 1: Geometric Characteristics of the Selected Signalized Roundabouts

Roundabout Name	Approach ID	Approach Direction	No. Entry Lane	Lane Width	Roundabout Diameter	Center Island Diameter	No. Lane of Roundabout	Lane Width of Roundabout
Al-Kafrawy	Approach 1	E/W	3	3.3	80	50	3	3.8
	Approach 2	N/S	3	3.3				
	Approach 3	W/E	3	3.3				
	Approach 4	S/N	3	3.3				
Al-Rwad	Approach 1	S/N	3	3.3	72	44	3	3.65
	Approach 2	E/W	3	3.3				
	Approach 3	N/S	3	3.3				
	Approach 4	W/E	3	3.3				
El-Nasagon El-Sharqion	Approach 1	E/W	3	3.3	75	51	3	3.3
	Approach 2	N/S	3	3.3				
	Approach 3	W/E	3	3.3				
	Approach 4	S/N	3	3.3				
El-Safera	Approach 1	W/E	3	3.3	56	26	3	3.8

	Approach 2	S/N	3	3.3				
	Approach 3	E/W	3	3.3				
	Approach 4	N/S	3	3.3				

2.4. Field Delay Extraction

Field delay data were extracted from the recorded videos for each selected roundabout, approach, and study period. Delay was calculated as the difference between actual travel time and free-flow travel time for the same movement path. Vehicle travel times were measured by tracking vehicles through the observation section, while free-flow time represented uncongested conditions. These field delay values served as the main reference for assessing existing performance and comparing the observed conditions with VISSIM outputs, HCM estimates, and improvement scenarios.

2.5. HCM Delay Estimation

The HCM delay procedure was applied as an analytical method to estimate control delay. Although it is mainly developed for conventional signalized intersections, it was used in this study to examine its applicability to signalized roundabouts, which involve additional operational effects such as circulating flow interaction, entry and exit behavior, weaving movements, roundabout geometry, and circulating lanes.

According to the HCM signalized intersection method, average control delay is calculated using delay components. Uniform delay represents delay under stable flow and uniform vehicle arrivals during the signal cycle and was calculated using Eq. (1).

$$d_1 = \frac{0.5C(1-\frac{g}{C})^2}{1-[\frac{\min(1,x)g}{C}]} \qquad (1)$$

Where X is volume-to-capacity ratio of the subject lane, C is the cycle length, and g is the effective green time for the phase.

The incremental delay component represents the additional delay caused by random vehicle arrivals, temporary oversaturation, and cycle failures. It is calculated using Eq. (2).

$$d_2 = 900T[(X-1)+\sqrt{(X-1)^2+\frac{8kIX}{C\,T}} \qquad (2)$$

Where X is Degree of saturation, V/C ratio, T is analysis time period (hour), K is Incremental delay factor, I is Upstream filtering/metering adjustment factor, C is Capacity of the facility.

The initial queue delay was assumed to be zero because no residual queue from a previous analysis period was considered. Therefore, the total HCM delay was calculated by combining the uniform and incremental delay components only. The resulting delay values, expressed in seconds per vehicle, were compared with the field and VISSIM delay results.

2.6. Base Case VISSIM Model

VISSIM was used as the microscopic simulation tool because it can represent individual vehicle movements and complex interactions at signalized roundabouts, including entry–circulating flow interaction, lane changing, queue formation, speed reduction, and signal control effects. Since these characteristics are difficult to capture using analytical methods alone, VISSIM provided a more realistic representation of existing traffic conditions.

The base-case models were calibrated by comparing simulated delay values with field delay measurements. When differences were observed, selected parameters were adjusted to improve model accuracy. These parameters included driving behavior settings, desired speed distributions, reduced speed areas, and conflict area settings, as they directly affect vehicle movement, gap acceptance, merging, queues, and delay. Calibration was therefore necessary before using the models for delay comparison and operational improvement analysis.

After completing the VISSIM model coding, including geometry, traffic inputs, vehicle routes, conflict areas, signal control settings, and simulation parameters, the models were run to simulate the existing traffic operation at the selected signalized roundabouts. The simulation aimed to reproduce actual vehicle movements, approach interactions, queue formation, and delay conditions under the observed traffic demand.

The main output extracted from the VISSIM models was the average vehicle delay for each approach during each study period. Delay values were collected after the warm-up period to ensure that the results reflected stable simulation conditions rather than initial loading effects. These outputs were organized for each selected roundabout and used in the following comparison and evaluation stages with the field and HCM delay results, as shown in Figure 4

Figure 4: Simulation Run of the VISSIM Model

3.Results and Discussions

3.1.Traffic Volume Results

The analysis focuses on identifying peak traffic demand, variations between study periods, dominant movement directions, and approach-level traffic patterns. These characteristics are important for understanding the traffic operation of each roundabout and for interpreting queue formation and delay conditions.

- ***Al-Kafrawy Signalized Roundabout***

Traffic volume results for Al-Kafrawy Signalized Roundabout showed clear variation across the study periods, ranging from 5,729 to 10,278 PCU/hr. The lowest volume was recorded during the mid-day period on 20/12/2025, while the highest volume occurred during the afternoon peak on 28/12/2025. This peak demand, about 79.4% higher than the lowest recorded volume, represents the most critical operating condition and indicates that roundabout performance is strongly influenced by time-dependent traffic demand. Turning movement distributions also varied by approach, as shown in Table 2, the turning movement pattern at Al-Kafrawy Roundabout varied by approach. Approach 1 was mainly affected by left-turn traffic, Approach 3 by right-turn traffic, while through movements were dominant at Approaches 2 and 4. Overall, through traffic represented the main movement at the roundabout, especially during the peak period due to the high demand on Approaches 2 and 4. These results indicate that total traffic volume alone is not sufficient to assess performance, as directional movement distribution strongly affects approach delays, queue formation, and overall operation.

Table 2: Directional Traffic Volume Distribution at Al-Kafrawy Signalized Roundabout

Name	Date	Time	Direction		
			Left	Through	Right
Approach 1	20/12/2025	10:00 AM - 11:00 AM	491	255	98
	20/12/2025	12:00 PM - 1:00 PM	554	197	88
	28/12/2025	3:00 PM - 4:00 PM	737	326	236
	28/12/2025	4:00 PM - 5:00 PM	874	760	321
	30/12/2025	3:00 PM - 4:00 PM	661	531	247
Approach 2	20/12/2025	10:00 AM - 11:00 AM	75	1586	122
	20/12/2025	12:00 PM - 1:00 PM	159	1723	80
	28/12/2025	3:00 PM - 4:00 PM	64	1921	131
	28/12/2025	4:00 PM - 5:00 PM	84	2273	166
	30/12/2025	3:00 PM - 4:00 PM	53	1897	166
Approach 3	20/12/2025	10:00 AM - 11:00 AM	113	248	346
	20/12/2025	12:00 PM - 1:00 PM	115	194	315
	28/12/2025	3:00 PM - 4:00 PM	64	217	493
	28/12/2025	4:00 PM - 5:00 PM	119	414	757
	30/12/2025	3:00 PM - 4:00 PM	131	428	660
Approach 4	20/12/2025	10:00 AM - 11:00 AM	326	1566	798
	20/12/2025	12:00 PM - 1:00 PM	183	1623	498
	28/12/2025	3:00 PM - 4:00 PM	351	2047	1270
	28/12/2025	4:00 PM - 5:00 PM	614	2092	1804
	30/12/2025	3:00 PM - 4:00 PM	528	1842	1454

- ***Al-Rwad Signalized Roundabout***

Traffic volume results for Al-Rwad Signalized Roundabout showed clear variation across the study periods, ranging from 5,386 to 7,938 PCU/hr. The lowest volume was recorded during the mid-day period on 22/12/2025, while the highest volume occurred during the afternoon period on the same day. Although Al-Rwad recorded a lower peak volume than Al-Kafrawy, some approaches showed more critical delay conditions, indicating that total traffic volume alone does not fully explain operational performance.

Turning movement distributions varied by approach, Table 3. Through movements were dominant at all approaches, with the highest through demand observed at Approach 3 during the peak period. Approaches 1 and 3 generally carried higher through volumes, while Approaches 2 and 4 had lower demand with noticeable right-turn movements. These results indicate that Al-Rwad mainly served through traffic, and that both total volume and directional distribution should be considered when interpreting delay results and identifying critical approaches.

Table 3: Directional Traffic Volume Distribution at Al-Rwad Signalized Roundabout

Name	**Date**	**Time**	**Direction**		
			Left	**Through**	**Right**
Approach 1	22/12/2025	12:00 PM - 1:00 PM	167	1389	201
	22/12/2025	2:00 PM - 3:00 PM	390	1763	288
	22/12/2025	3:00 PM - 4:00 PM	303	1756	215
	29/12/2025	1:00 pm - 2:00 pm	338	1474	209
	30/12/2025	4:00 pm - 5:00 pm	259	1651	192
Approach 2	22/12/2025	12:00 PM - 1:00 PM	254	577	253
	22/12/2025	2:00 PM - 3:00 PM	347	803	445
	22/12/2025	3:00 PM - 4:00 PM	323	870	429
	29/12/2025	1:00 pm - 2:00 pm	275	536	213
	30/12/2025	4:00 pm - 5:00 pm	306	781	381
Approach 3	22/12/2025	12:00 PM - 1:00 PM	371	1168	105
	22/12/2025	2:00 PM - 3:00 PM	415	1863	109
	22/12/2025	3:00 PM - 4:00 PM	392	2251	78
	29/12/2025	1:00 pm - 2:00 pm	292	1406	123
	30/12/2025	4:00 pm - 5:00 pm	356	1923	94
Approach 4	22/12/2025	12:00 PM - 1:00 PM	144	449	308
	22/12/2025	2:00 PM - 3:00 PM	134	584	377
	22/12/2025	3:00 PM - 4:00 PM	192	745	384
	29/12/2025	1:00 pm - 2:00 pm	119	436	320
	30/12/2025	4:00 pm - 5:00 pm	165	625	369

- ***El-Nasagon El-Sharqion Signalized Roundabout***

Traffic volume results for El-Nasagon El-Sharqion Signalized Roundabout showed relatively stable demand compared with Al-Kafrawy and Al-Rwad, ranging from 5,526 to 6,062 PCU/hr. The lowest volume was recorded during the afternoon period on 29/12/2025, while the highest volume occurred on 28/12/2025 from 1:00 PM to 2:00 PM. This limited variation indicates that the roundabout operated under a more consistent demand level during the selected periods.

However, turning movement distributions varied by approach, as shown in Table 4. Through movements were generally dominant at Approaches 1, 2, and 4, while Approach 3 was mainly dominated by left-turn traffic. This clear directional imbalance, especially the high left-turn demand at Approach 3, may increase vehicle interaction inside the roundabout and contribute to higher delay and queue formation. Therefore, the delay performance at this roundabout is expected to be influenced more by movement distribution than by changes in total traffic volume alone.

Table 4: Directional Traffic Volume Distribution at Nasagon El-Sharqion Signalized Roundabout

Name	Date	Time	Direction		
			Left	Through	Right
Approach 1	28/12/2025	12:00 PM - 1:00 PM	101	745	157
	28/12/2025	1:00 PM - 2:00 PM	50	864	142
	29/12/2025	3:00 PM - 4:00 PM	76	812	270
	29/12/2025	4:00 pm - 5:00 pm	99	845	264
	31/12/2025	4:00 pm - 5:00 pm	85	843	243
Approach 2	28/12/2025	12:00 PM - 1:00 PM	169	734	615
	28/12/2025	1:00 PM - 2:00 PM	95	743	588
	29/12/2025	3:00 PM - 4:00 PM	189	616	536
	29/12/2025	4:00 pm - 5:00 pm	113	599	493
	31/12/2025	4:00 pm - 5:00 pm	130	649	527
Approach 3	28/12/2025	12:00 PM - 1:00 PM	1393	736	71
	28/12/2025	1:00 PM - 2:00 PM	1531	799	117
	29/12/2025	3:00 PM - 4:00 PM	1459	785	86
	29/12/2025	4:00 pm - 5:00 pm	1466	743	82
	31/12/2025	4:00 pm - 5:00 pm	1488	750	92
Approach 4	28/12/2025	12:00 PM - 1:00 PM	289	732	21
	28/12/2025	1:00 PM - 2:00 PM	402	708	23
	29/12/2025	3:00 PM - 4:00 PM	212	480	5
	29/12/2025	4:00 pm - 5:00 pm	377	616	17
	31/12/2025	4:00 pm - 5:00 pm	334	588	16

- ***El-Safera Aziza Signalized Roundabout***

Traffic volume results for El-Safera Aziza Signalized Roundabout showed moderate variation across the study periods, ranging from 4,914 to 6,259 PCU/hr. The lowest volume was recorded on 25/12/2025 from 1:00 PM to 2:00 PM, while the peak volume occurred on the same day from 3:00 PM to 4:00 PM. Although this roundabout recorded lower total volumes than Al-Kafrawy and Al-Rwad, traffic demand remained relatively high during the afternoon peak periods.

Turning movement distributions varied by approach, as shown in Table 5. Through movements were dominant at all approaches, with Approaches 2 and 4 carrying the highest through traffic volumes. Although some left-turn and right-turn movements were observed, they were generally lower than the through movements. These results indicate that El-Safera Aziza mainly served through traffic, and its operational performance was primarily influenced by peak-period through demand, particularly at Approaches 2 and 4.

Table 5: Directional Traffic Volume Distribution at El-Safera Aziza Signalized Roundabout

Name	Date	Time	Direction		
			Left	**Through**	**Right**
Approach 1	25/12/2025	1:00 PM - 2:00 PM	147	622	238
	25/12/2025	2:00 PM - 3:00 PM	166	738	338
	25/12/2025	3:00 PM - 4:00 PM	214	747	334
	25/12/2025	4:00 pm - 5:00 pm	94	817	407
	31/12/2025	3:00 pm - 4:00 pm	170	791	370
Approach 2	25/12/2025	1:00 PM - 2:00 PM	197	780	157
	25/12/2025	2:00 PM - 3:00 PM	320	864	171
	25/12/2025	3:00 PM - 4:00 PM	418	1347	149
	25/12/2025	4:00 pm - 5:00 pm	460	1324	188
	31/12/2025	3:00 pm - 4:00 pm	422	1224	172
Approach 3	25/12/2025	1:00 PM - 2:00 PM	160	569	302
	25/12/2025	2:00 PM - 3:00 PM	186	717	155
	25/12/2025	3:00 PM - 4:00 PM	224	720	223
	25/12/2025	4:00 pm - 5:00 pm	239	644	201
	31/12/2025	3:00 pm - 4:00 pm	223	653	202
Approach 4	25/12/2025	1:00 PM - 2:00 PM	483	1077	182
	25/12/2025	2:00 PM - 3:00 PM	365	1112	232
	25/12/2025	3:00 PM - 4:00 PM	389	1240	254
	25/12/2025	4:00 pm - 5:00 pm	400	669	260
	31/12/2025	3:00 pm - 4:00 pm	386	936	253

3.2.Model Calibration and Validation

The VISSIM models were calibrated and validated to ensure that the simulated delay values represent the field conditions with acceptable accuracy. The field delay values were compared with the corresponding VISSIM delay values for the selected signalized roundabouts. The percentage error was calculated to evaluate the difference between the observed and simulated delay values. The calibration results are presented in **Error! Reference source not found.**, while the validation results are presented in **Error! Reference source not found.**.

The calibration results showed a clear improvement in the agreement between field and VISSIM delay values. The mean percentage error decreased from 18.58% before calibration to 6.23% after calibration, representing about a 66.5% improvement in model accuracy. In addition, the number of observations within the acceptable 10% error range increased from 10 out of 53 observations before calibration to 50 out of 53 after calibration.

For validation, 27 observations were used to test the calibrated model. The validation results showed a mean percentage error of 4.65%, with 26 out of 27 observations within the 10% error range. Overall, 76 out of 80 calibration and validation observations were within the acceptable range, with an overall mean percentage error of 5.70%. These results confirm that the calibrated VISSIM models reliably represent actual traffic conditions and can be used for delay analysis and comparison with HCM results.

Table 6: Results of Percent Error Measurements of Average Delay per Vehicle for Model Calibration

No. of Observations	**Average Delay (sec/veh)**					
	Before Calibration			**After Calibration**		
	Field	**VISSIM**	**Error (%)**	**Field**	**VISSIM**	**Error (%)**
1	23.4	27.2	16.12	23.4	25.1	7.12
2	25.7	30.1	17.17	25.7	27.1	5.43
3	35.2	41.9	18.96	35.2	33.7	4.23
4	144.1	161.1	11.76	144.1	155.5	7.89
5	58.7	66.5	13.27	58.7	64.5	9.86
6	25.2	29.7	17.95	25.2	25.8	2.46
7	91.7	106.9	16.54	91.7	99.6	8.53
8	97.4	105.2	8.03	97.4	98.5	1.11
9	39.2	49.7	26.65	39.2	43.1	9.83
10	65.5	81.1	23.91	65.5	71.2	8.78
11	19.8	22.3	12.81	19.8	20.1	1.68
12	31.3	38.5	22.87	31.3	33.6	7.23
13	19.4	24.3	25.33	19.4	19.8	2.12
14	37.6	46.1	22.56	37.6	38.3	1.73
15	28.1	40.5	44.22	28.1	30.2	7.54
16	28.1	30.2	7.60	28.1	27.2	3.20
17	28.0	33.3	18.98	28.0	30.2	7.90
18	40.0	47.2	18.12	40.0	36.3	9.13
19	31.2	35.2	12.81	31.2	33.3	6.72
20	38.5	42.2	9.55	38.5	40.2	4.36
21	28.6	31.8	11.35	28.6	30.6	7.05
22	25.6	29.1	13.64	25.6	25.4	0.98
23	81.4	95.7	17.55	81.4	88.8	9.05
24	141.8	131.2	7.47	141.8	131.5	7.26
25	106.9	125.8	17.73	106.9	119.2	11.56

26	34.7	42.2	21.46	34.7	38.1	9.53
27	160.1	179.1	11.85	160.1	173.3	8.25

Table 7: Continue

No. of Observations	Average Delay (sec/veh)					
	Before Calibration			After Calibration		
	Field	VISSIM	Error (%)	Field	VISSIM	Error (%)
28	174.8	194.2	11.09	174.8	185.5	6.09
29	29.3	37.9	29.32	29.3	32.2	9.87
30	147.9	162.4	9.81	147.9	156.3	5.70
31	15.0	19.3	28.51	15.0	14.4	4.10
32	12.7	17.3	36.47	12.7	13.5	6.49
33	12.1	15.4	27.37	12.1	13.1	8.39
34	8.7	11.1	28.06	8.7	9.2	6.14
35	14.2	15.3	8.02	14.2	13.6	3.86
36	18.2	19.2	5.68	18.2	18.0	1.04
37	19.8	22.2	12.12	19.8	20.3	2.43
38	78.6	95.3	21.28	78.6	84.3	7.28
39	98.8	104.1	5.41	98.8	99.2	0.43
40	65.2	78.2	19.93	65.2	65.8	0.91
41	18.3	25.5	39.61	18.3	18.8	2.86
42	14.9	18.6	25.14	14.9	16.2	8.99
43	12.5	15.5	23.94	12.5	13.2	5.55
44	19.1	22.3	17.02	19.1	21.2	11.25
45	24.8	30.2	21.62	24.8	26.7	7.54
46	20.7	27.9	34.76	20.7	19.2	7.26
47	99.5	116.9	17.50	99.5	109.7	10.27
48	96.8	111.4	15.04	96.8	105.3	8.71
49	28.2	35.5	25.83	28.2	30.6	8.62
50	103.1	112.6	9.23	103.1	104.1	0.95
51	119.2	134.7	13.00	119.2	131.1	9.96
52	101.2	124.8	23.32	101.2	109.2	7.90
53	131.4	119.3	9.19	131.4	122.0	7.10

Table 7: Results of Percent Error Measurements of Average Delay per Vehicle for Model Validation

No. of Observations	**Average Delay (sec/veh)**		
	Field	**VISSIM**	**Error (%)**
54	121.7	125.2	2.89
55	117.2	123.3	5.25
56	27.8	27.6	0.69
57	36.5	37.2	1.83
58	68.0	70.6	3.90
59	53.8	56.7	5.41
60	42.2	42.0	0.28
61	18.3	19.9	8.69
62	15.9	17.1	7.30
63	32.2	33.4	3.87
64	39.6	41.8	5.60
65	40.3	42.3	4.98
66	25.3	27.2	7.63
67	40.1	41.4	3.33
68	87.1	88.2	1.26
69	27.3	28.6	4.76
70	52.7	54.7	3.76
71	21.3	21.7	1.89
72	27.5	28.2	2.64
73	17.6	19.2	9.27
74	25.6	26.1	2.18
75	23.9	24.8	3.80
76	13.9	15.3	9.72
77	25.9	27.5	6.34
78	40.3	44.4	10.24
79	15.1	15.9	5.40
80	20.0	20.6	2.76

3.3.Delay Time Results

This section presents the delay results for the selected signalized roundabouts based on field measurements, calibrated VISSIM outputs, and HCM analysis. For each roundabout, delay values were compared graphically by approach and study period to evaluate the agreement between the different methods.

The HCM delay values were estimated using the signalized intersection procedure, which was originally developed for conventional signalized intersections. However, signalized roundabouts involve additional operational effects such as circulating flow interaction, entry behavior, weaving movements, and geometric influences. Therefore, differences may occur between HCM delay estimates and the field or VISSIM results

- ***Al-Kafrawy Signalized Roundabout***

The delay comparison for Al-Kafrawy Signalized Roundabout was conducted at the approach level using field, calibrated VISSIM, and HCM delay results, as shown in Figure 5. The results indicate that Approaches 1 and 2 experienced the highest delays, especially during the peak period from 4:00 PM to 5:00 PM on 28/12/2025. Approach 1 recorded the highest field delay of 144.1 s/veh, compared with 155.5 s/veh from VISSIM and 225.4 s/veh from HCM. Approach 2 also showed a high field delay of 141.8 s/veh, with corresponding VISSIM and HCM values of 131.5 s/veh and 140.1 s/veh.

In contrast, Approaches 3 and 4 recorded lower delay values, indicating that the operational problems were mainly concentrated at the first two approaches. Overall, the calibrated VISSIM results closely followed the field delay trend, while the HCM method tended to overestimate delay, particularly under congested conditions. This confirms that the calibrated VISSIM model provided a better representation of observed delay conditions at Al-Kafrawy Roundabout.

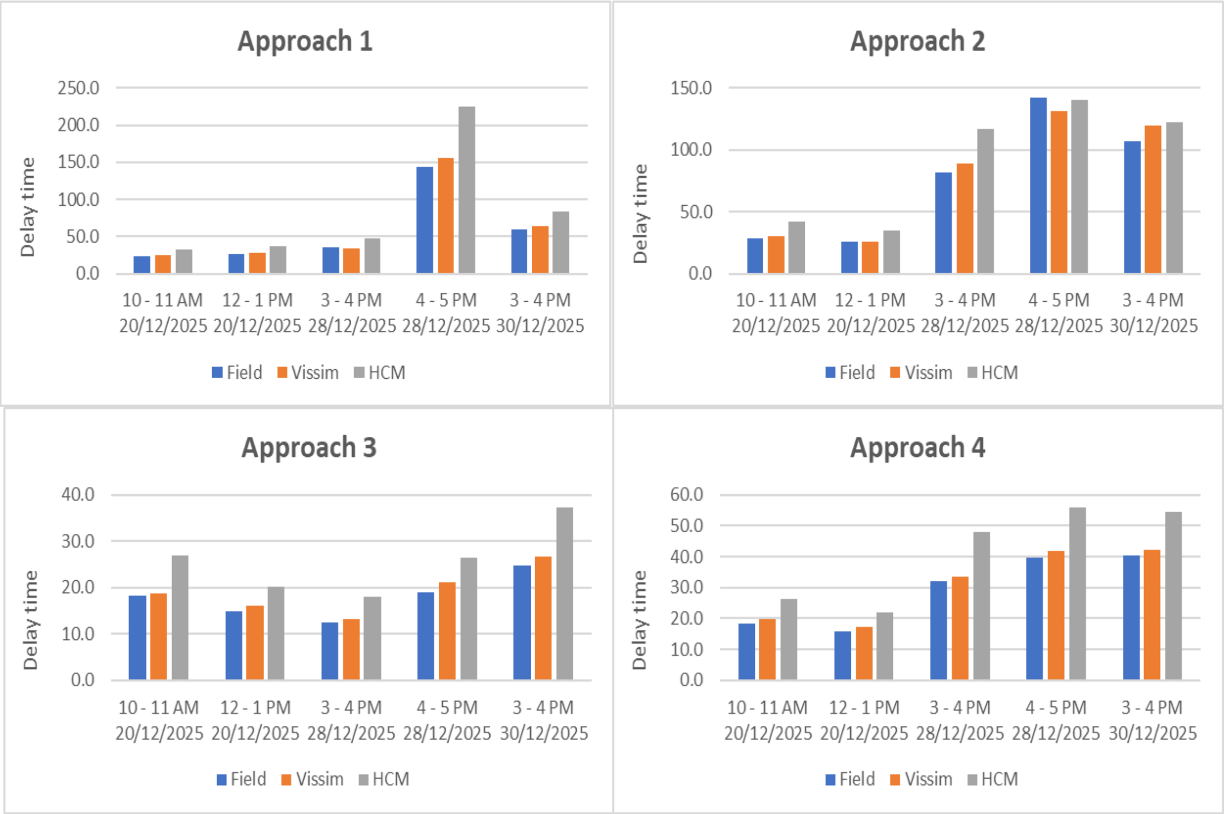


Figure 5: Delay Time Comparison at Al-Kafrawy Signalized Roundabout

- ***Al-Rwad Signalized Roundabout***

The delay comparison for Al-Rwad Signalized Roundabout was conducted using field, calibrated VISSIM, and HCM delay results, as shown in Figure 6. The results show that Approach 2 recorded the highest delay values, particularly during the afternoon peak period. The most critical condition occurred on 22/12/2025 from 3:00 PM to 4:00 PM, with a field delay of 174.8 s/veh, compared with 185.5 s/veh from VISSIM and 167.2 s/veh from HCM. Approach 2 also recorded a high field delay of 160.1 s/veh during the previous hour, confirming it as the most critical approach.

Approaches 1 and 3 also experienced relatively high delays, reaching maximum field delays of 97.4 and 103.1 s/veh, respectively, while Approach 4 generally showed lower delay values. Overall, the calibrated VISSIM results closely followed the field delay trend, with an average delay of 76.6 s/veh compared with 72.3 s/veh in the field. The HCM method showed a higher average delay of 93.5 s/veh and generally overestimated delay, except at Approach 2 during the most critical period. These results indicate that VISSIM provided better agreement with field measurements, while the main delay problem was concentrated at Approach 2.

Figure 6: Delay Time Comparison at Al-Rwad Signalized Roundabout

- ***El-Nasagon El-Sharqion Signalized Roundabout***

The delay comparison for El-Nasagon El-Sharqion Signalized Roundabout was conducted using field, calibrated VISSIM, and HCM delay results, as shown in Figure 7. The results indicate that Approach 3 recorded the highest delay values and represented the critical approach. The maximum field delay occurred on 29/12/2025 from 3:00 PM to 4:00 PM, reaching 131.4 s/veh, compared with 122.0 s/veh from VISSIM and 129.3 s/veh from HCM. Approach 3 also showed consistently high delays during the other study periods.

In contrast, Approaches 1, 2, and 4 recorded lower delay values, with Approach 2 showing the lowest delay levels. Overall, the calibrated VISSIM results closely followed the field delay trend, with an average delay of 46.8 s/veh compared with 45.3 s/veh in the field. The HCM method produced a higher average delay of 58.2 s/veh and generally overestimated delays at most approaches, although it was close to field values at Approach 3 during high-delay periods. These results confirm that VISSIM provided better agreement with field measurements, while the roundabout performance was mainly controlled by Approach 3.

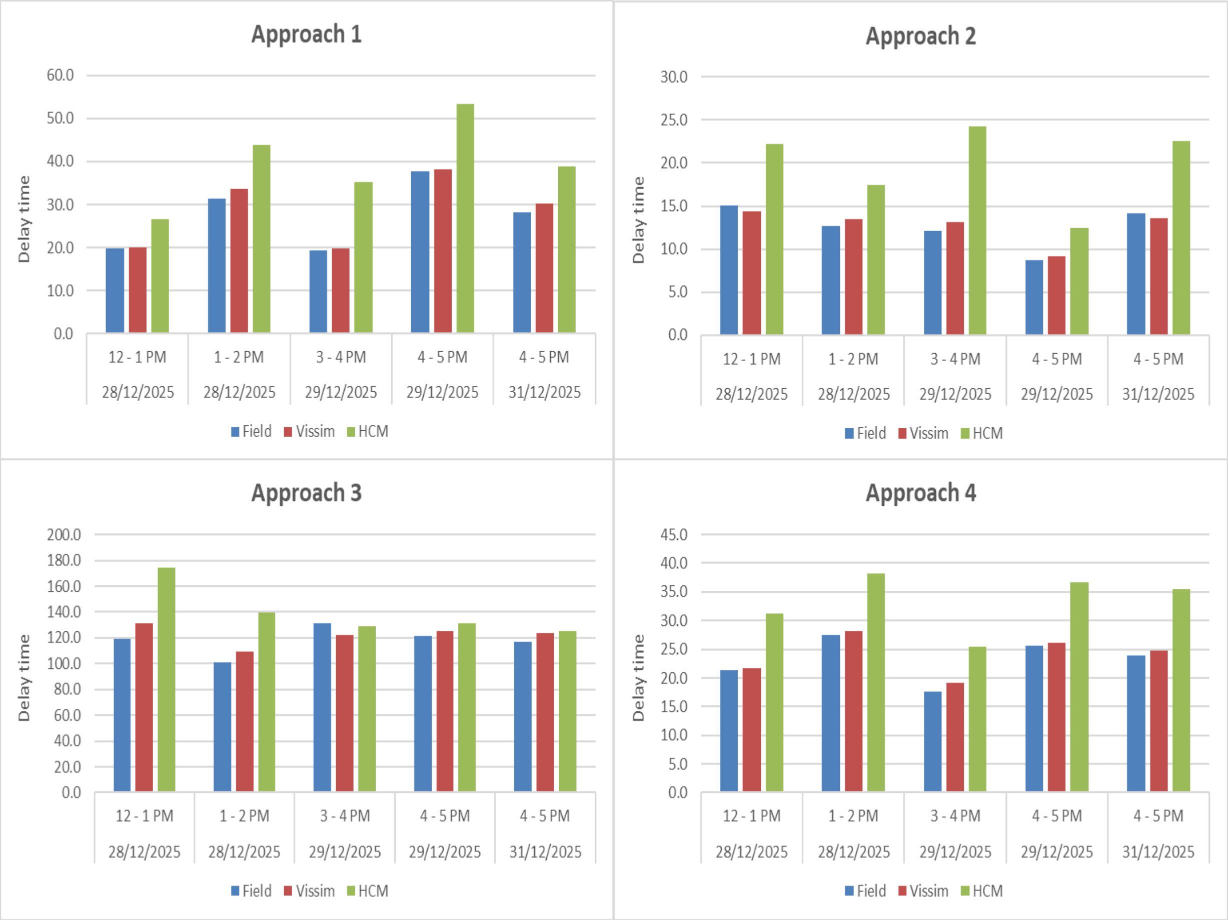


Figure 7: Delay Time Comparison at El-Nasagon El-Sharqion Signalized Roundabout

- ***El-Safera Aziza Signalized Roundabout***

The delay comparison for El-Safera Aziza Signalized Roundabout was conducted using field, calibrated VISSIM, and HCM delay results, as shown in Figure 8. The results show that Approach 2 recorded the highest delay values, particularly during the afternoon peak period. The maximum field delay occurred on 25/12/2025 from 4:00 PM to 5:00 PM, reaching 98.8 s/veh, compared with 99.2 s/veh from VISSIM and 142.3 s/veh from HCM. This confirms that Approach 2 was the most critical approach.

Approach 3 also showed relatively high delays during some periods, with a maximum field delay of 68.0 s/veh from 3:00 PM to 4:00 PM on 25/12/2025. In contrast, Approach 4 generally recorded the lowest delays, while Approach 1 showed moderate delay levels. Overall, the calibrated VISSIM results closely followed the field delay trend, with an average delay of 40.6 s/veh compared with 39.5 s/veh in the field. The HCM method produced a higher average delay of 57.1 s/veh and generally overestimated delay, especially during peak periods. These results indicate that VISSIM provided better agreement with field measurements, while operational performance was mainly affected by Approaches 2 and 3.

Figure 8: Delay Time Comparison at El-Safera Aziza Signalized Roundabout

3.4. Delay Correlation and Regression Analysis

Statistical analysis was conducted to evaluate the agreement between field delay measurements, calibrated VISSIM outputs, and HCM estimates. Descriptive statistics were used to summarize the delay results using mean, standard deviation, minimum, and maximum values, while correlation analysis was used to examine the relationship between field delays and the estimated values from VISSIM and HCM.

The mean field delay was 50.61 ± 41.44 s/veh, compared with 52.92 ± 43.48 s/veh for calibrated VISSIM and 67.39 ± 49.91 s/veh for HCM. The calibrated VISSIM mean delay was only 2.31 s/veh higher than the field value, representing a 4.6% difference, while the HCM mean delay was 16.78 s/veh higher, representing a 33.2% increase. Minimum, maximum, and standard deviation values showed the same trend, confirming that VISSIM closely reflected both the magnitude and variability of field delays, whereas HCM generally produced higher and more dispersed delay estimates.

The correlation results are summarized in Table 8. Field and calibrated VISSIM delays showed a very strong significant correlation, with $r = 0.997$ and $p < 0.001$, as shown in Figure 9. The regression equation was $y = 1.0458x - 0.0092$, with $R^2 = 0.9937$, indicating that 99.37% of the variation in VISSIM delay was explained by field delay. The slope was close to 1.0, confirming that the calibrated VISSIM model closely followed the observed field delay pattern.

Field and HCM delays also showed a strong significant correlation, with $r = 0.965$ and $p < 0.001$, as shown in Figure 10. The regression equation was $y = 1.1618x + 8.5827$, with $R^2 = 0.9303$. Although this indicates a strong relationship, the lower R^2 value and wider scatter show that HCM estimates were more dispersed than VISSIM results. The slope greater than 1.0 and the positive intercept also indicate that HCM generally overestimated field delay.

Overall, the statistical analysis confirms that calibrated VISSIM delay results were closer to field measurements than HCM estimates. While HCM followed the general field delay trend, it produced higher and more variable delay values. Therefore, the calibrated VISSIM model is considered more reliable for representing actual delay conditions at the selected signalized roundabouts.

Table 8: Correlation between Field Delay and Estimated Delay Values

Reference delay	Compared delay	r value	p value	Significance
Field	**VISSIM**	0.997	< 0.001	Significant
Field	**HCM**	0.965	< 0.001	Significant

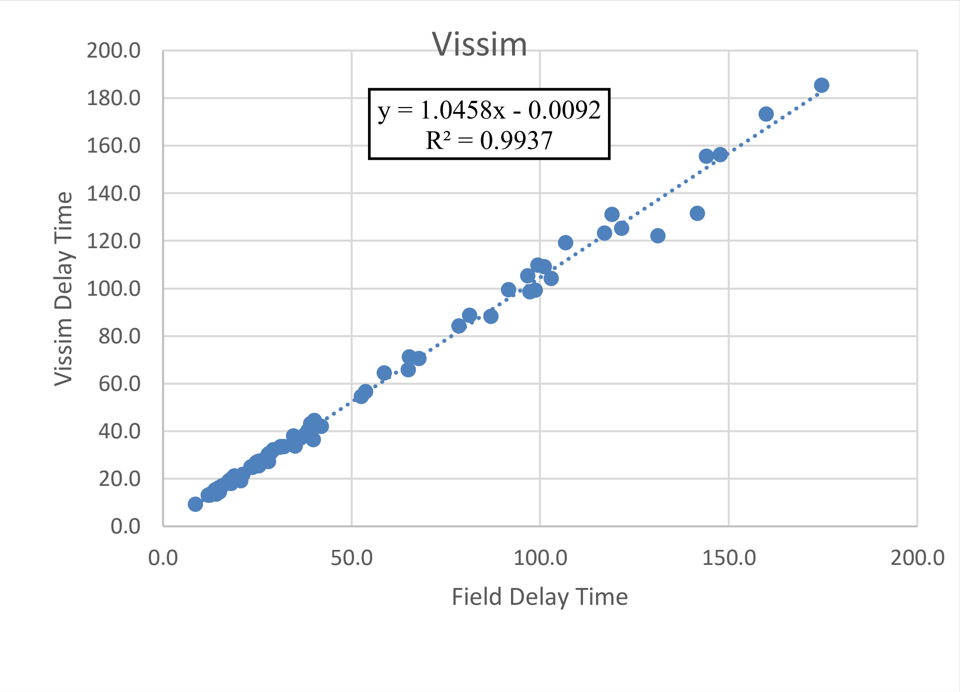


Figure 9: Scatter Plot between Field Delay and VISSIM Delay

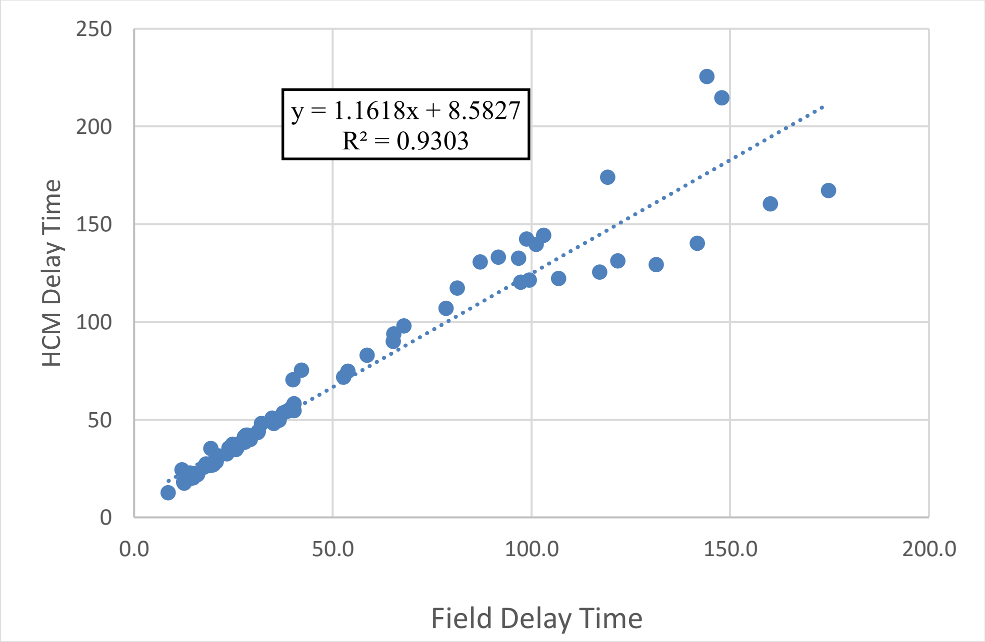


Figure 10: Scatter Plot between Field Delay and HCM Delay

3.5. Enhancement Scenarios

After evaluating the base-case delay results and identifying the critical conditions, two VISSIM-based enhancement scenarios were tested for the selected signalized roundabouts. Scenario 1 optimized the existing signal timing while maintaining the current roundabout geometry. The improvement focused on adjusting cycle lengths and green time distribution to reduce delay at critical approaches, representing a low-cost operational solution.

Scenario 2 converted the signalized roundabouts into conventional signalized intersections. This scenario involved a major operational and geometric change by removing circulating movements and reducing weaving, entry–exit conflicts, and circulating flow interactions. It was mainly tested to examine whether a direct signalized intersection layout could improve performance, especially where through traffic was dominant.

The scenarios were evaluated at the roundabout level using average delay, level of service (LOS), and delay reduction percentage. LOS was classified according to the HCM criteria, as shown in Table 9. The base case and the two enhancement scenarios were then compared to assess the achieved improvement. Average delay and LOS results are presented in Table 10, while delay reduction percentages for Scenarios 1 and 2 are shown in Figure 11.

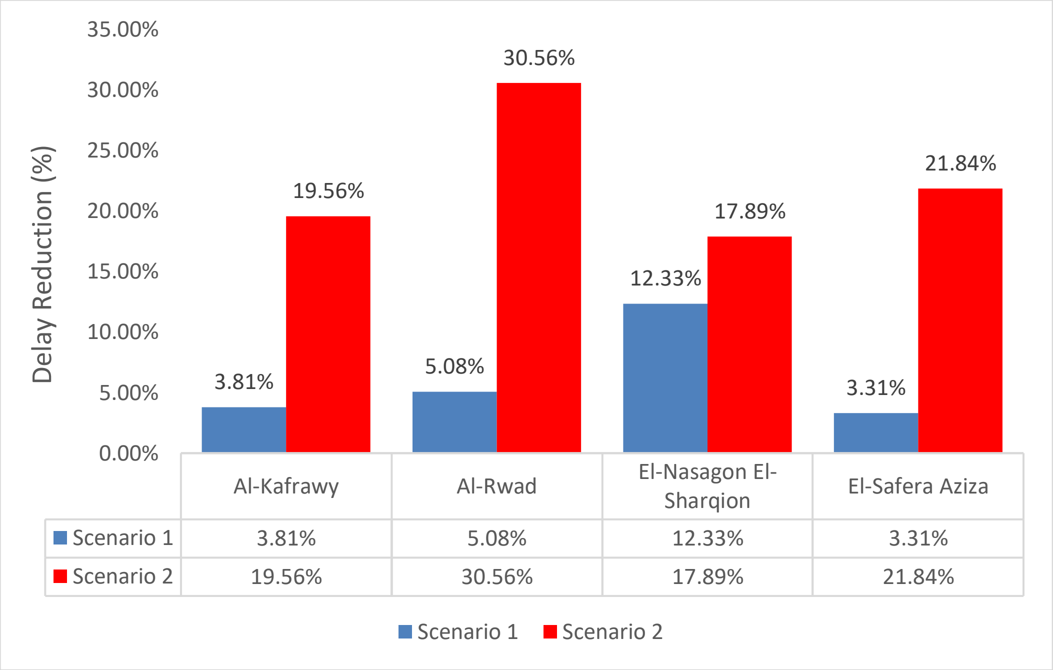
Table 9: LOS Criteria for Signalized Intersections [17].

LOS	Control Delay per Vehicle (s/veh)
A	≤ 10
B	> 10–20
C	> 20–35
D	> 35–55
E	> 55–80
F	> 80

Table 10: Average Delay and LOS on the Selected Intersections for Different Scenarios

Roundabout Name	Scenario	Average Delay (sec/veh)	LOS
Al-Kafrawy	Base Case Scenario	80.27	F
	Scenario 1	77.21	E
	Scenario 2	64.57	E
Al-Rwad	Base Case Scenario	114.20	F
	Scenario 1	108.40	F
	Scenario 2	79.30	E
El-Nasagon El-Sharqion	Base Case Scenario	56.46	E
	Scenario 1	49.50	D
	Scenario 2	46.36	D

El-Safera Aziza	Base Case Scenario	63.14	E
	Scenario 1	61.05	E
	Scenario 2	49.35	D



	Al-Kafrawy	Al-Rwad	El-Nasagon El-Sharqion	El-Safera Aziza
🟦 Scenario 1	3.81%	5.08%	12.33%	3.31%
🟥 Scenario 2	19.56%	30.56%	17.89%	21.84%

Figure 11: Delay Reduction for Enhancement Scenarios

As shown in Table 10 and Figure 11, both enhancement scenarios reduced the average delay compared with the base case for all selected roundabouts. However, Scenario 2 achieved greater delay reductions, ranging from 17.89% to 30.56%, while Scenario 1 produced smaller reductions ranging from 3.31% to 12.33%. This indicates that converting the signalized roundabouts into conventional signalized intersections was generally more effective than signal timing optimization alone.

At Al-Kafrawy, the base case delay was 80.27 s/veh with LOS F. Scenario 1 reduced the delay to 77.21 s/veh and improved LOS to E, while Scenario 2 further reduced it to 64.57 s/veh with LOS E. At Al-Rwad, which recorded the highest base delay of 114.20 s/veh, Scenario 1 reduced the delay slightly to 108.40 s/veh, while Scenario 2 reduced it to 79.30 s/veh and improved LOS from F to E. For El-Nasagon El-Sharqion, Scenario 1 reduced delay from 56.46 to 49.50 s/veh, while Scenario 2 further reduced it to 46.36 s/veh, with both scenarios improving LOS from E to D. At El-Safera Aziza, Scenario 2 also produced a larger improvement, reducing delay from 63.14 to 49.35 s/veh and improving LOS from E to D, while Scenario 1 achieved only a minor reduction.

The stronger performance of Scenario 2 is mainly related to the dominance of through traffic at several approaches. In the existing roundabout layout, through vehicles still interact with entering, circulating, and exiting traffic, increasing travel time, queues, and delay. Converting the layouts into conventional signalized intersections made through movements more direct and reduced circulating flow interaction, weaving, and entry–exit conflicts. Overall, Scenario 2 provided the greatest delay reduction at all selected roundabouts, while Scenario 1 offered limited but useful low-cost improvements.

4.Conclusions and Recommendations

4.1.Conclusions

The main conclusions of this study can be summarized as follows:

- The selected signalized roundabouts showed different traffic and operational characteristics, confirming the need to evaluate each location separately based on traffic demand, movement distribution, and approach performance. Al-Kafrawy recorded the highest peak traffic volume of 10,278 PCU/hr, followed by Al-Rwad with 7,938 PCU/hr, while El-Nasagon El-Sharqion and El-Safera Aziza showed lower and more stable demand.
- Directional movement analysis showed that through traffic was dominant at Al-Rwad and El-Safera Aziza, while Al-Kafrawy had a more unbalanced pattern and El-Nasagon El-Sharqion was strongly affected by left-turn traffic at Approach 3. Delay results showed that operational problems were concentrated at specific approaches, with Al-Rwad Approach 2 recording the highest field delay of 174.8 s/veh.
- Calibration and validation confirmed the reliability of the VISSIM models. The mean percentage error decreased from 18.58% to 6.23% after calibration, and 95.0% of observations were within the acceptable error range. The mean VISSIM delay was only 4.6% higher than field delay, while the HCM mean delay was 33.2% higher, indicating that HCM generally overestimated delay.
- Correlation analysis confirmed stronger agreement between field and VISSIM delays than between field and HCM delays, with $R^2 = 0.9937$ and $R^2 = 0.9303$, respectively. Therefore, HCM should be applied with caution for signalized roundabouts because it may not fully represent circulating flow interaction, weaving movements, entry behavior, and geometric effects.
- The improvement scenarios showed that signal timing optimization reduced delay by 3.31% to 12.33%, while converting the roundabouts into conventional signalized intersections achieved larger reductions of 17.89% to 30.56%. The greatest improvement occurred at Al-Rwad, where delay decreased from 114.20 to 79.30 s/veh and LOS improved from F to E. Overall, calibrated VISSIM was effective for evaluating signalized roundabouts, and Scenario 2 was the most effective alternative, especially where through traffic was dominant.

4.2.Recommendations

The recommendations of this study can be summarized as follows:

1. Field data collection using video recording is recommended for signalized roundabout studies, as it allows accurate extraction of traffic volumes, vehicle classifications, turning movements, and delay values. Delay should also be evaluated at both roundabout and approach levels, because critical delay conditions may be concentrated at specific approaches rather than reflected in the overall average delay.
2. The HCM signalized intersection delay procedure should be applied with caution for signalized roundabouts, as it may overestimate delay and may not fully capture circulating flow interaction, weaving movements, and geometric effects. Therefore, calibrated microscopic simulation models such as VISSIM are recommended, since they can more realistically represent vehicle interactions, driver behavior, lane changing, signal control, and geometry.
3. Signal timing optimization may be used as a low-cost short-term improvement, particularly during peak periods. However, its effect may be limited when delays are mainly caused by geometry, circulating movements, or unbalanced demand. In such cases, converting a signalized roundabout into a conventional signalized intersection may be considered, especially when through traffic is dominant and delay is caused by weaving and entry–exit conflicts. This alternative should be tested using calibrated simulation models before implementation.
4. Finally, improvement plans should focus on the critical approaches identified from the analysis rather than applying the same treatment to the whole roundabout, since approach-level delay conditions can vary significantly within the same intersection.

Future studies are recommended to include additional performance measures, such as queue length, travel time, number of stops, fuel consumption, emissions, and safety indicators, to provide a more comprehensive evaluation of signalized roundabout performance. Further research should also focus on developing or calibrating analytical delay models specifically for signalized roundabouts, since the HCM signalized intersection procedure may not fully represent their operational characteristics. In addition, the proposed methodology should be applied to more signalized roundabouts in other urban areas to verify its applicability under different traffic demands, geometric layouts, and signal control conditions.

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