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Turbo Design as a Countermeasure for Traffic Safety and Operation at Roundabouts

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Abstract

Turbo roundabouts have recently been developed in various nations due to their numerous benefits. The paper assesses the safety and efficiency of turbo roundabouts. Replacement is done without damaging private property. Evaluations are performed by using two simulations. VISSIM is used to evaluate operational performance by identifying delays and service levels. SSAM 3.0 evaluates safety performance by identifying two conflict-severity indexes: the time-to-collision (TTC) and post-encroachment time (PET). Turbo roundabouts improve the level of service (LOS) compared to multi-lane ones. In the Al-Mohafda roundabout, LOS is changed from LOS F to LOS D, reducing vehicle delays by 66%. In addition, Al-Tarbia and Said Al-Assar roundabouts (LOS) changed from (LOS F) to (LOS E), reducing vehicle delays by 55% and 63%, respectively. Turbo roundabouts have superior traffic operating safety. TTC increased by 41% at the Al Mohafada and Al-Tarbia roundabouts, which are classified as high-risk to medium-risk roundabouts, and increased by 33% at the Said Al-Assar roundabouts. The total number of conflicts decreased by 69%, 74%, and 85% at the three roundabouts (Al-Tarbia, Saeed Al Asar, and Al Mohafada), respectively. Legislators may thoroughly study proposed legislation and work towards integrating turbo roundabouts as a potential solution for intersections.

Keywords: Level of Service, Post-Encroachment Time, Road Safety, Time to Collision, Turbo-Roundabouts.

1. Introduction

A roundabout is an intersection in which traffic flows around a central island. A roundabout may have one circular lane, two circular lanes, or multiple circulation lanes [1], [2]. Roundabouts are a proven safety countermeasure for intersection safety [3] and are considered traffic-calming measures [4]. However, primarily single-lane roundabouts achieve the above benefits, as international regulations prohibit multilane roundabouts. However, two- or three-lane roundabouts are still used worldwide. The main disadvantage of these configurations is that they create dangerous conflict points at the ring-road roundabout that do not exist in single-lane configurations, significantly reducing vehicle safety [5]. Drivers in multilane roundabouts, for example, prefer to use the outer circulatory lane in all driving directions and avoid the inner circulatory lane, which leads to incorrect confrontations at roundabout exits. Aside from that, cars often take the quickest path across the circulation highway, ignoring many lane markers [6]. To solve this problem, several new types of roundabouts have been developed, some of which are now used almost worldwide, others only in certain countries, and others still in use or under development [7], [8]. Turbo roundabouts are an emerging multi-lane roundabout design successfully implemented in Europe [9]. The Netherlands chose turbo roundabouts as an alternative to multilane roundabouts. Many countries in Europe, South America, Canada, and South Africa have about 468 turbo roundabouts worldwide, 344 of which are in the Netherlands [10].

A turbo roundabout differs from a traditional roundabout in that it redirects vehicles into different lanes before they enter the circuit. Once in the circuit, it separates and isolates traffic heading in different directions. Traffic efficiency has improved, but there are only merging problems in the turbo roundabout. Turbo roundabouts first appeared in the Netherlands in 2000. According to the Dutch practical handbook and guidelines, turbo roundabouts are classified into 7 types based on the number of legs, bypasses, and entry and exit passages. The four-legged turbo roundabouts can be configured into five variants: basic, egg, knee, spiral, and spinner. Three-leg turbo roundabouts have two types: the extended knee and the star [11].

Czech researchers compare European laws and practices regarding the safety and efficacy of turbo roundabout design. Furthermore, they presented their study findings and field measurements for approximately 100 turbo roundabouts in nine European countries. The results from these studies validate that assessing traffic conflicts in road design is essential to improving traffic safety and sustainable transportation [12]. Conventional multi-lane roundabout replacement with a turbo roundabout is increasing, and studies have demonstrated their superiority over the traditional scheme [13]. Researchers studied the assessment and operation of turbo roundabouts in the Czech Republic; turbo roundabouts provide various advantages (greater capacity, traffic continuity, reduced accident rates) and are well-founded [14]. The turbo roundabout is suggested as an alternative to a high-volume, very crowded multilane roundabout. The complicated traffic operation of the current and prospective multilane roundabouts, as well as the high traffic and aggressive driving behavior common in Doha, Qatar, are modeled by Verkehr in Städten – Simulations model {VISSM}. The suggested designs show significant advantages over the traditional design and provide an overall improved Level of Service (LOS) [15].

The turbo roundabout's capacity, which includes a two-lane loop, is limited. Consequently, experts consistently propose several alternative designs for turbo roundabouts featuring multilane loops. This design is better suited for crossings that experience significant traffic demand [16], [17]. Turbo roundabouts may be equipped with signal controllers. The operating performance of signalized turbo roundabouts is superior to that of signalized intersections [18]. It's crucial to analyze the safety of turbo roundabouts. Specifically, it is necessary to talk about the severity of crashes at turbo roundabouts [19], [20]. Microsimulation models can also assess the level of road network safety. The Federal Highway Administration (FHWA) developed the Surrogate Safety Assessment Model (SSAM) software, which processes vehicle trajectories (location, speed, and acceleration profiles) generated during simulation to automate conflict analysis. Thus, several writers identified plausible connections between the conflicts identified by the SSAM and actual incidents, even though the SSAM required precise calibration of the traffic model [21].

All the works included a comparison between a regular roundabout or a signalized junction and a turbo roundabout, and implemented the simplest spinner version. The turbo roundabout comprises inlets that accommodate either a single or two lanes. The current work evaluates three substantial conventional roundabouts. One roundabout has three lanes, while the other two have more than three. Three roundabouts in the city of Karbala (Iraq) are chosen and modified for the work to meet various requirements for turbo roundabouts.

Karbala has many multi-lane roundabouts that manage substantial traffic despite aggressive driving. Consequently, the typical roundabout must be revised to accommodate the existing traffic load. As urbanization progresses, the road network will include more intersections and intricate operations. Despite its recent introduction, the turbo design has not yet gained widespread use as an alternative in Iraq. This work investigates whether motion separation principles in turbo roundabouts can be applied to multi-lane roundabouts to replace conventional roundabouts that experience high traffic volumes, delays, and long queues. The work compares the operational and safety performance of multi-lane and turbo roundabouts using simulation software (VISSIM) and safety analysis software (SSAM).

The main objective is to investigate the effects of converting three large-scale traditional roundabouts into a turbo roundabout. To introduce this advanced type of roundabout for consideration and verification as an alternative solution for intersections in need of improvement.

2. Methods

The sample comprised three multi-lane, four-leg roundabouts in the urban center of the Kerbala district (CKD). Fig.1 illustrates the sequence of the three roundabouts. Characterized by traffic issues such as long queues, significant delays during peak hours, and aggressive driving behavior [22]. A performance study analyzed these three roundabout types: vehicle delay and the level of service at each roundabout. This work used PTV VISSIM, 2024, Student Edition, to simulate traffic interaction. The outputs from the VISSIM TRJ file simulation will serve as inputs to the SSAM software to evaluate traffic safety. Fig. 2 shows the methods of the work.

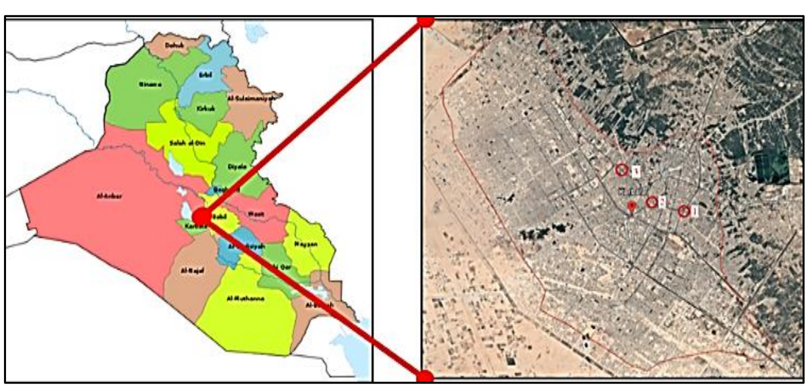


Figure 1. Location of the three studied roundabouts in Kerbala City.

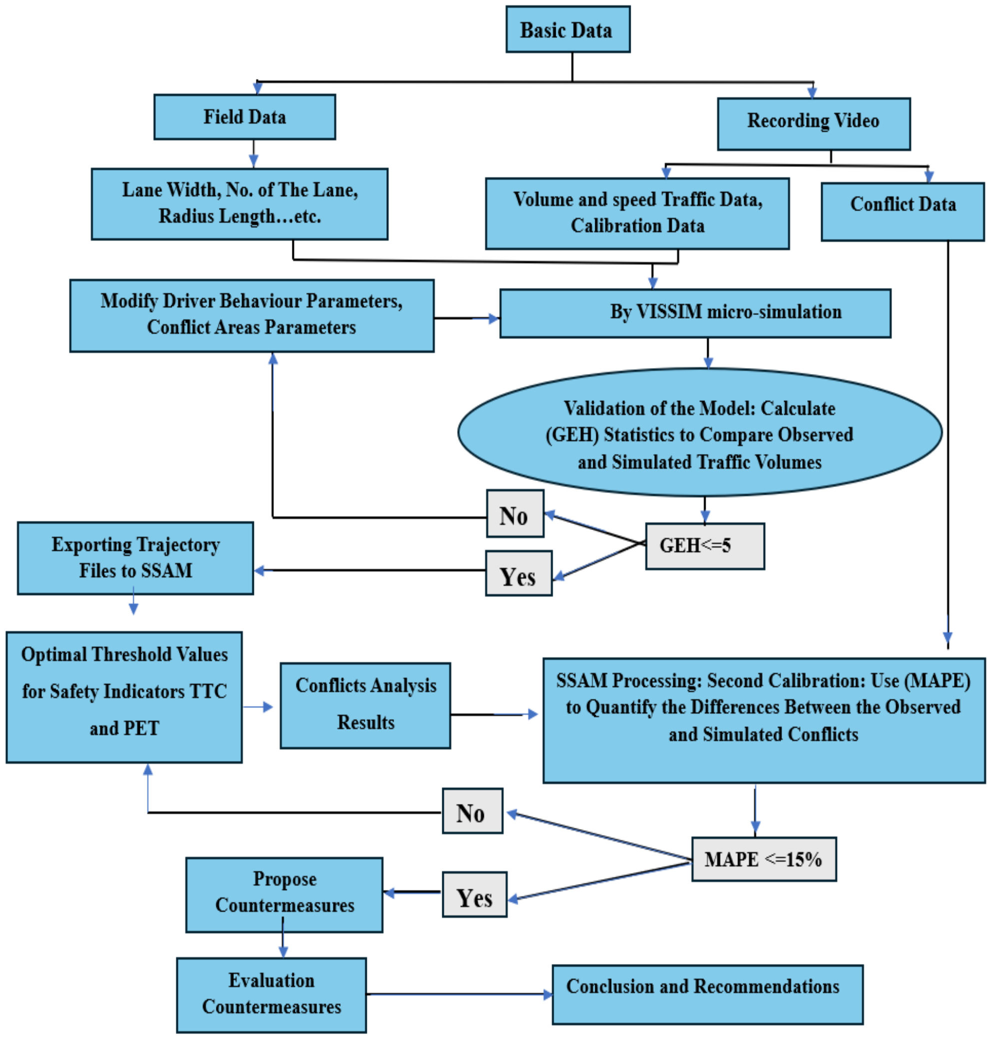


Figure 2. Work Methods Diagram.

2.1. Data Collection

The data has been separated into Geometric data, Traffic volume data, and Traffic conflict data. VISSIM microsimulation uses the first geometric and traffic volume data and the second data collection step (traffic conflict data) as the basis for the field study to validate the model.

2.1.1. Geometric data

Accurately describing the geometry, which is determined by the number of approaches, the width of the lane (m), the roundabout diameter (m), and the center island (m) diameter, is of the utmost importance. Table 1 presents all the geometric details for simulating the three roundabouts.

Table 1. Geometric features of the three roundabouts.

Roundabout Name	Approach Direction	No. Lane	Width of Lane (m)	Diameter (m)	No. Lane	Width of Lane of Roundabout (m)
	NE	3	4			
	NW	3	3.5			
Al-Tarbia	SE	5	3	91	5	3.5
	SW	3	3.5			
	NW	3	3.5			
	SW	2	3.5			
Said Al-Assar.	E	3	3.5	78	3	4
	SE	3	4			
	NW	5	2.5			
Al-mohafda	SE	4	3			
	SW	3	3	45	5	3.5

2.1.2. Traffic volumes

Collecting traffic volume data is essential for accurately simulating real-world conditions. Traffic volume is collected for the peak hours from 07:30 to 08:30 AM, 12:30 to 01:30 PM, and 07:30 to 08:30 PM over four days throughout the week. During the period from Sunday, October 1, 2023, to Saturday, October 7, 2023. Traffic modes are classified into light vehicles, heavy vehicles, motorcycles, three-wheelers, and minibuses. (Fig.3, Fig.4 and Fig.5) shows the peak-hour traffic volume at the studied roundabouts, including traffic flow designated as right Turns, left turns, through turns, and U-turns.

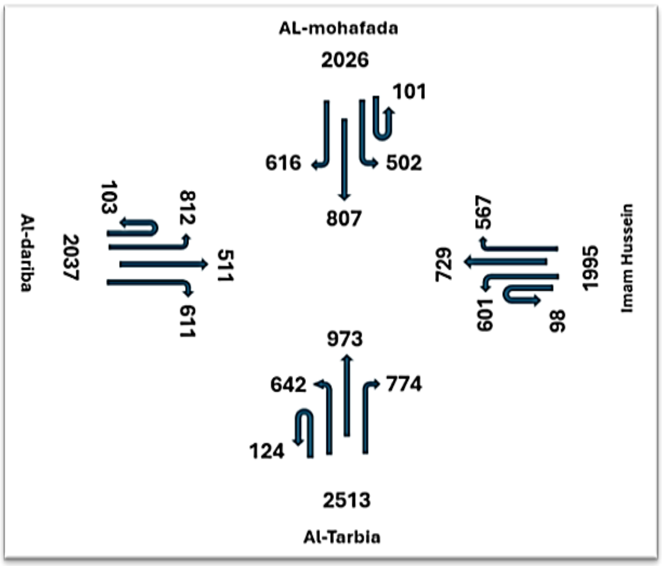


Figure 3. Peak hour volume (19:30-20:30) at Al-Tarbia roundabout.

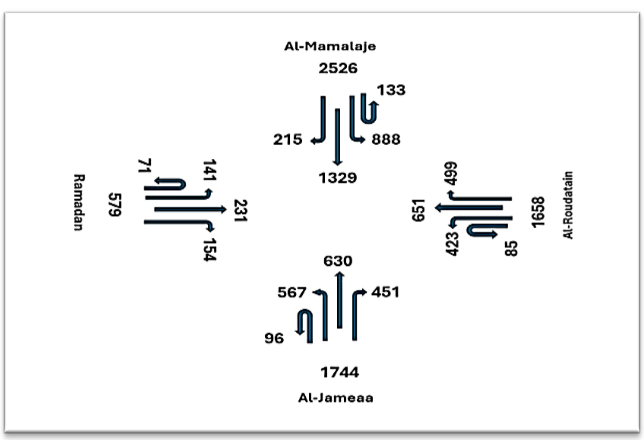


Figure 4. Peak hour volume (19:30-20:30) at Said Al-Assar roundabout.

2.1.3. Traffic conflict data

Traffic conflict data can be collected through video [19]. Data is collected from surveillance cameras that record traffic volumes to obtain information about the occurrence of traffic conflicts in the field. It also calibrates the model by comparing simulated conflicts with observed conflicts. Conflicts are observed at the entry, exit, and circular portions of the roundabout to compare the observed and simulated conflict counts accurately. Many conflicts are recorded by observing the preventive measures taken by road users to avoid accidents, such as breakdowns, changing direction, and using brakes to reduce vehicle speed. Other manifestations include sudden deviations from vehicle routes or lane changes, which are considered components of the lane-changing conflict—i.e., the classification of disputes based on the criteria presented by [23], [24]. During simulated conflicts, SSAM found conflict sites in three categories: rear-end (0 to 30 degrees), lane-change (30 to 80 degrees), and crossing (80 to 180 degrees), as shown in Fig. 6 [25].

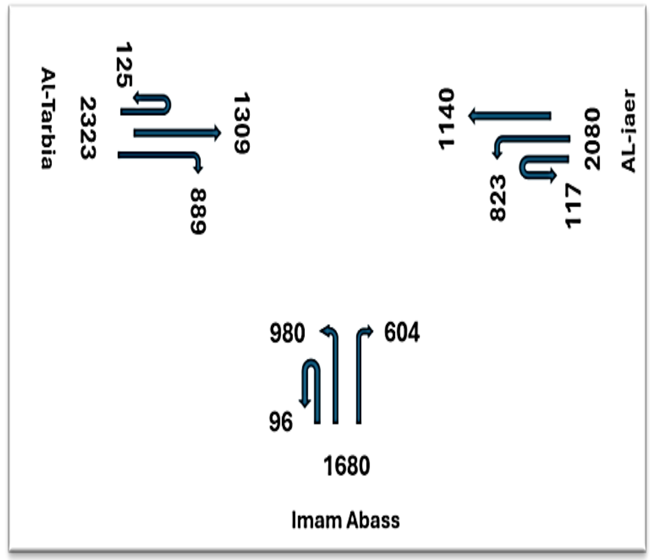


Figure 5. Peak Hour Volume (12:30 - 13:30) at Al-Mohafada roundabout.

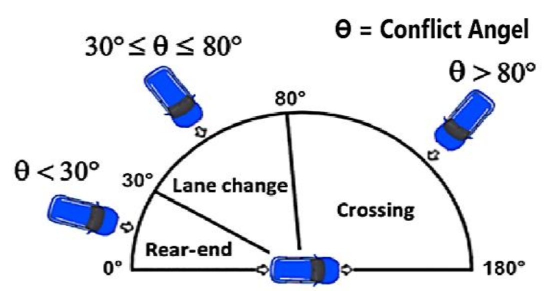


Figure 6. Conflict angle threshold.

2.2. Microsimulation Modelling

VISSIM is a traffic simulation tool that accurately models complex roundabout traffic operations and is sensitive to the replication of driver behavior [26]. VISSIM's priority rules and conflict areas features allow traffic modelers to adjust gap acceptance parameters. In other words, using priority rules and conflict-area features, VISSIM allows manual adjustment of gap-acceptance parameters at roundabouts. The reduced-speed area feature will enable users to model normal vehicle behavior at roundabouts by slowing to 25–40 km/h as drivers approach the roundabout to start circulating the central island [27]. VISSIM allows traffic modelers to specify lane drivers' routes, which is crucial for modeling turbo roundabouts. VISSIM's default driving behavior creates a homogeneous traffic condition, requiring calibration to replicate actual field conditions. Calibration involves adjusting parameters. Calibration and validation processes used Geoffrey E. Haven (GEH) statistics to ensure accuracy, with a GEH value below 5 indicating a good fit [28]. The VISSIM model is calibrated manually through a trial-and-error process, individually modifying each parameter, such as lane change, car-following models, priority rules, and conflict areas, until the simulation model achieves the calibration target. Transportation departments widely use the formula as an empirical method to compare two independent traffic volume datasets. The formula used for the "GEHi Statistic" is.

$$\text{GEHi} = \sqrt{\frac{2(\text{m}-\text{C})^2}{\text{m}+\text{C}}} \quad (1)$$

m = simulation hourly traffic volume (vehicles per hour); c = field hourly traffic volume (vehicles per hour).

Used the mean absolute percent error (MAPE) to compare observed and simulated conflicts, which you can estimate using the following equation,

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{C_m^i - C_f^i}{C_f^i}\right| \quad (2)$$

Where n represents the number of observations, C_m^i represents the number of the simulated conflicts for time intervals i and$C_f^i$is the number of traffic conflicts observed in the field during the time interval i. Finally, Table 2 summarizes the most influential calibration parameters in VISSIM.

Table 2. VISSIM calibration parameters for the studied roundabout.

VISSIM parameter	Default value	Calibrated value Al-Tarbia	Calibrated value, Said Al-Assar	Calibrated value Al-Mohafda t
Average standstill distance (m)	2	1.2	1.1	1.3
Additive part of the safety distance	2	1	1	1
The multiplicative part of the safety distance	3	1.9	2	2.6
Front gap (sec)	0.5	0.6	0.1	0.5
Rear gap (sec)	0.5	0.6	0.1	0.5
Safety distance factor (Conflict areas) (m)	1.5	1	1	1
Minimum gap time (sec)	3.2	2.6	2.4	3
Lock ahead distance (m)	(0-250)	(75-150)	(70-160)	(85-200)
Lock back distance (m)	(0-150)	(15-75)	(13-65)	(15-85)

2.3. VISSIM Micro-Simulation Software

VISSIM Typology Modeling is as follows:

- Creating a network through links and connectors.
- Input traffic volumes and speed distribution.
- Define vehicle compositions (car, HGV, three-wheel vehicle).
- Determine all vehicle routes from one link to multiple links.
- Identify conflict areas and priority rules.
- Identify driver behavior parameters such as (lane change and car-following models).

3. Results

3.1. Model Validation

The VISSIM model's validation approach uses GEH statistics with values less than 5.0, as shown in Table 3. The model has minimal relative error when comparing simulated and observed conflicts, indicating adequate calibration. However, calibration is complex because the observer's perception determines field confrontations, which are stressful because they require constant attention and observation during heavy traffic.

Table 3. GEH statistical calculations for model validation.

Roundabout	Movement	m	c	GEH statistic
Al-Tarbia	NE entry	2358	2513	3.140781
	NW entry	2027	2037	0.221839
	SE entry	1858	2026	3.812279
	SW entry	1971	1995	0.538952
Said Al-Assar	NW entry	1366	1485	3.151834
	SW entry	522	579	2.429384
	E entry	2492	2565	0.678779
	SE entry	1631	1658	0.665805
Al-Mohafda	NW entry	1566	1680	2.829734
	SE entry	2222	2323	2.1187
	SW entry	2075	2080	0.109698

*GEH< 5 indicates a successful calibration by [28].

The MAPE value has been reduced from 57% to 20% for back-end conflicts, 54% to 25% for transport conflicts, 50% to 24% for redirect conflicts, and 46% to 14% for global transport conflicts. The conditions are met when the calculated MAPE is 15% or less. [29].

3.2. Roundabout and Alternative Design Turbo Roundabout

Typically, turbo roundabout designs differ significantly from traditional multilane roundabout designs. This design employs elevated lane dividers to separate the circulation lanes, thereby preventing movement within them and reducing weaving. Moreover, using lane dividers enhances the efficiency of all entrance lanes compared to the standard lane allocation in the old design. To depart the turbo roundabout in the intended direction, motorists must choose their lanes before entering. However, several types of turbo roundabouts prohibit U-turns. Traffic signs and lane markings significantly impact the traffic flow at turbo roundabouts. to showcase the layout of both conventional roundabouts and turbo roundabouts, as stated below.

3.2.1. Al-Tarbia Roundabout

The alternative design, the turbo roundabout, has four entrances and two exits per approach. As shown in Fig.7.

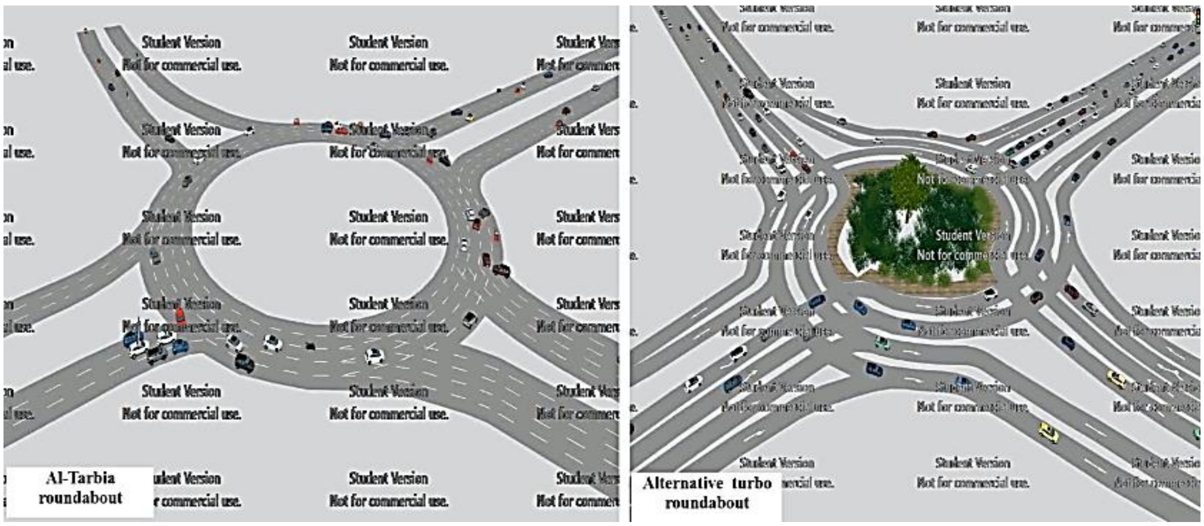


Figure 7. Al-Tarbia roundabout and the alternative turbo roundabout design.

3.2.2. Said Al-Assar

The alternative design, the turbo roundabout, has three entrances and two exits for each approach, as shown in Fig. 8.

3.2.3. Al-Mohafda Roundabout

The alternative design turbo roundabout has three entrances and two exits for two approaches, and the remaining approach has four entrances and three exits, as shown in Fig. 9.

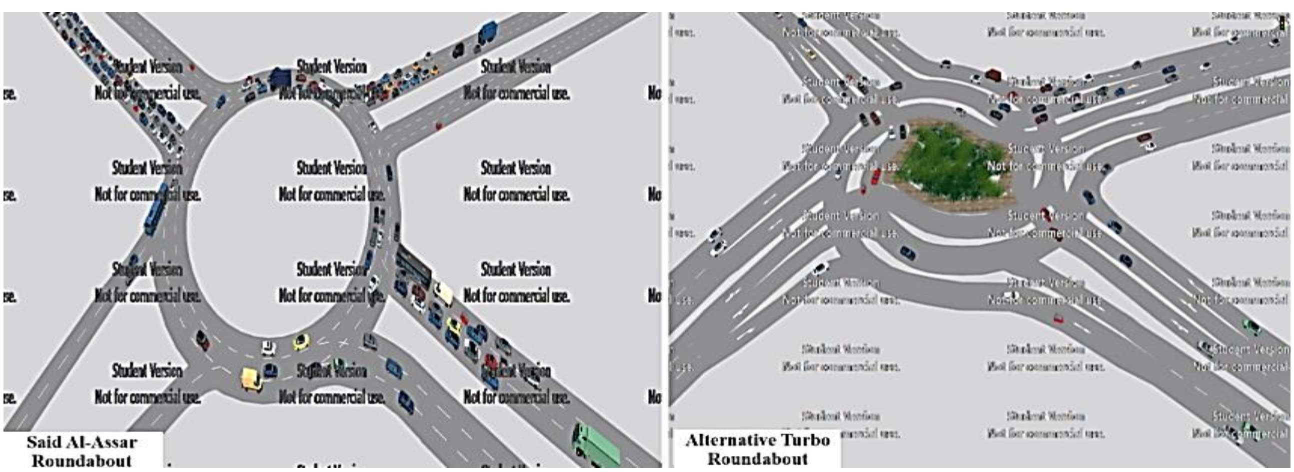


Figure 8. Said Al-Assar roundabout and the alternative turbo roundabout design.

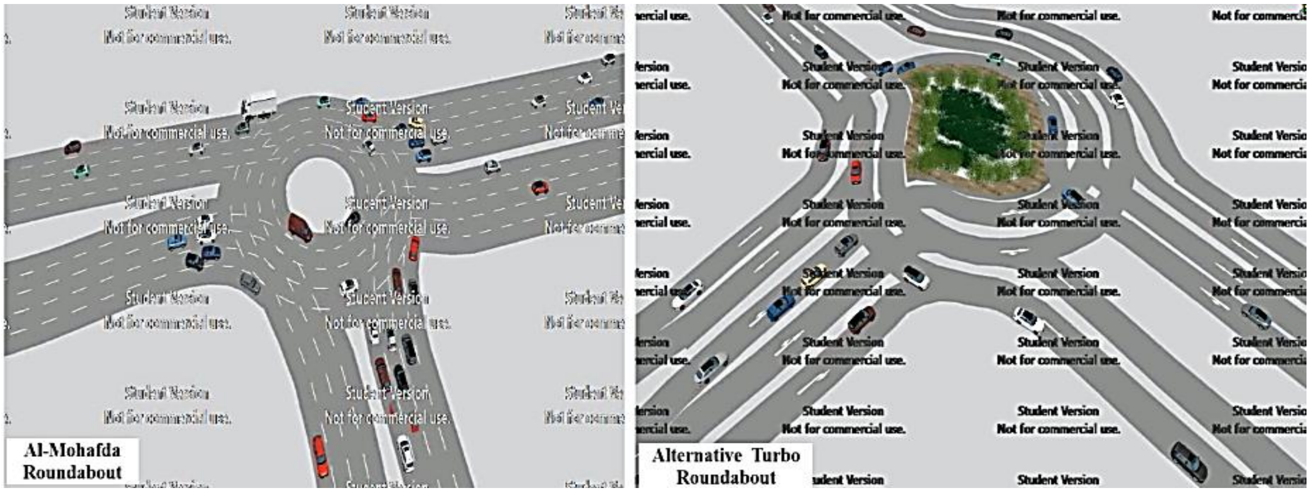


Figure 9. Al-Mohafda roundabout and the alternative turbo roundabout design.

3.3. Safety Analysis Measure

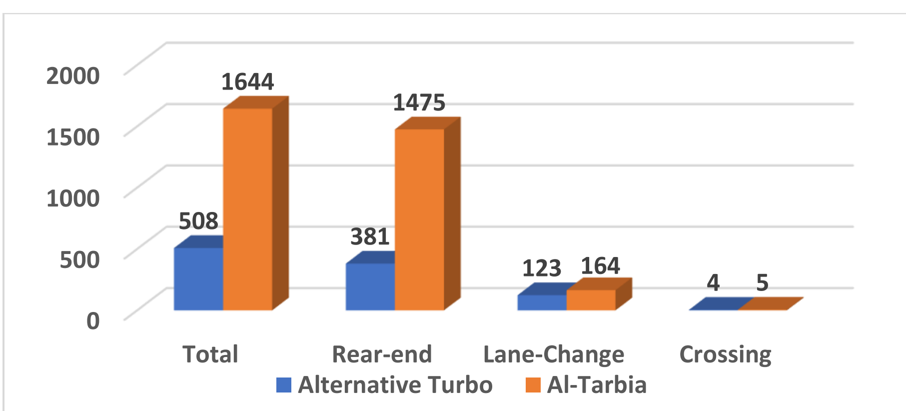
Each roundabout shows the location and type of likely traffic conflicts. The time-to-collision (TTC) and post-encroachment time (PET) have the most impact on SSAM findings after multiple tests [30]. (TTCmin)—the minimum time-to-collision value (in seconds) observed during the conflict for two vehicles to collide if speeds and directions do not change [31], [32]. (PET)—the time (in seconds) between when the first vehicle last occupied a position and the time when the second one arrived at the same position [33]. Despite VISSIM's continuous improvement, it still generates virtual crashes that lead to events with a TTC_{min} of 0. Data are queried in SSAM using filters for conflict types and a specific surrogate threshold ($0<TTC \leq 1.5s$). For the PET, conflicts were specified as 0.1 s < PET < 5 s [34].

3.3.1. Results for the number and type of surrogate safety

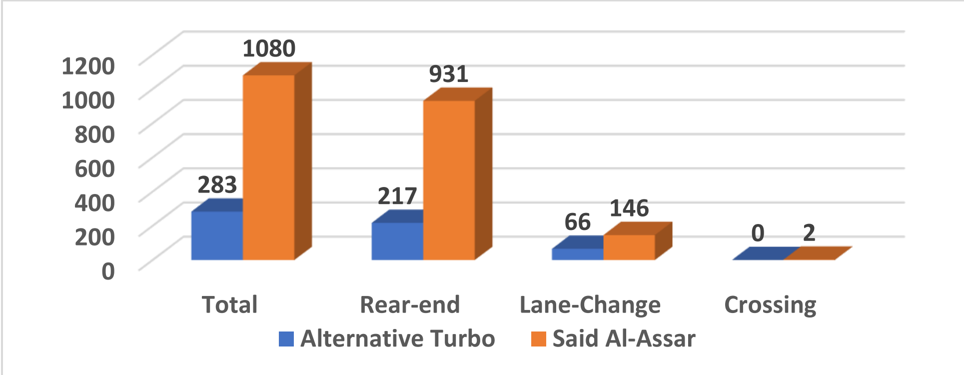
Fig. 10 compares the three roundabouts (Al-Tarbia, Said Al-Assar, and Al-Mohafda) with alternative turbo roundabouts. The results translate into percentage changes favoring the turbo roundabout for three roundabouts (Al-Tarbia, Saeed Al Asar, and Al Mohafada) of 69%, 74%, and 85%, respectively. (In a turbo roundabout, the inner and outer lanes do not intersect. These results are considered satisfactory compared with previous studies and are similar to those of this work. A substantial reduction in the total number of traffic conflicts (85%), especially rear-end conflicts (95%), was reported [35]. The turbo roundabout presented 72% fewer total roundabout collisions, underscoring the safety benefits of this new design [36].

3.3.2. Results for surrogate safety indicators

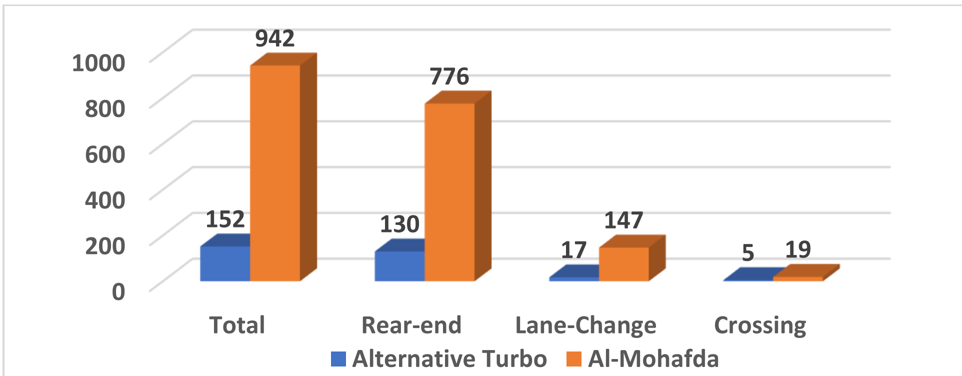
SSAM results in surrogate safety indicators at the three roundabouts (Al-Tarbia, Saeed Al Asar, and Al Mohafada) compared with the alternative turbo roundabout, as shown in Fig.11 and Fig.12.



(A)



(B)



(C)

Figure 10. Type and number of conflicts for A) Al-Tarbia roundabout, B) Saeed Al Asar roundabout, and C) Al Mohafada roundabout versus the alternative turbo roundabout.

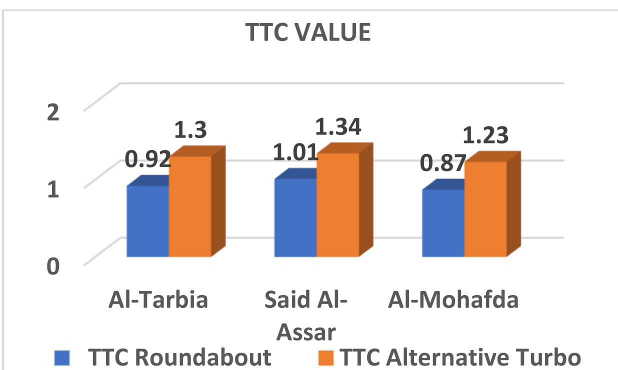


Figure 11. Surrogate safety indicators (TTC) for the roundabout and the alternative turbo roundabout.

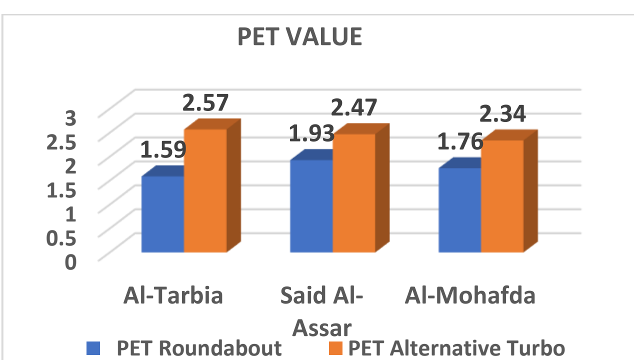


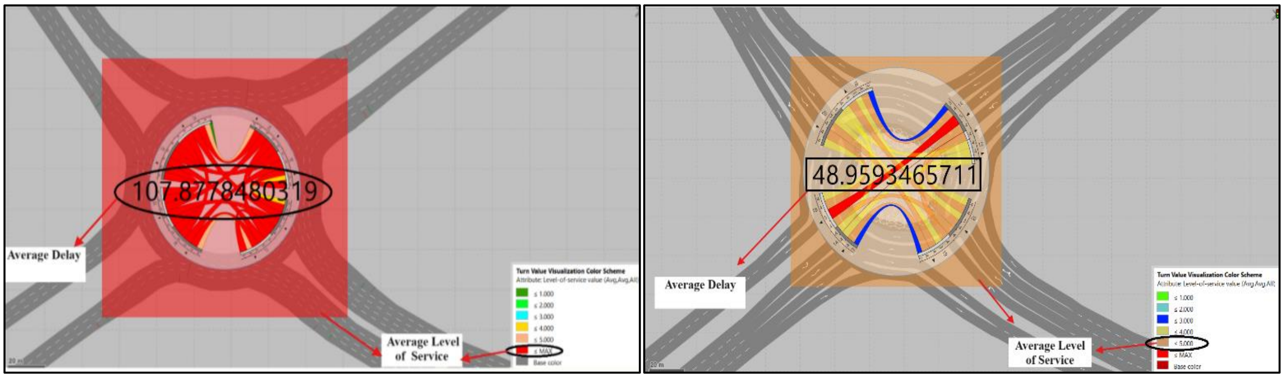
Figure 12. Surrogate safety indicators (PET) for three roundabouts and turbo alternatives.

Before considering alternatives, the Al Mohafada and Al-Tarbia roundabouts are classified as high-risk intersections with a TTC < 1. In contrast, Saeed Al Asar is classified as a medium-risk roundabout with a TTC>1. Following the procedure, the alternatives shifted in favor of the turbo roundabouts; TTC increased by 41% at Al Mohafada and Al-Tarbia roundabouts and by 33% at Saeed Al-Asar roundabouts, and the roundabouts were classified as medium risk due to their severity. The critical PET threshold should exceed the TTC [37]. Low PET values indicate a high severity of expected crashes [38]. In general, TTCmin and PET present lower values at the turbo-roundabout; this agrees with the results obtained by [20] and [36].

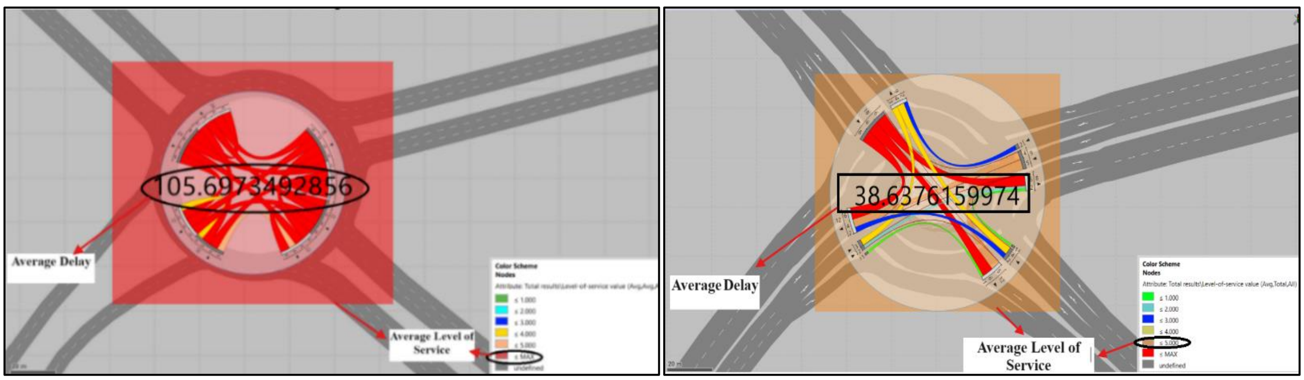
3.4. Comparison of Operational Performance Results

Compare the three roundabouts by checking parameters related to the level of service and delay. Fig. 13 compares operational performance, as measured by VISSIM output, at the three roundabouts (Al-Tarbia, Saeed Al Asar, Al Mohafada) with that of the alternative turbo roundabout.

Fig. 14 and Fig. 15 show the average delay and average service values for the Al-Tarbia, Saeed Al Asar, and Al Mohafada roundabouts before and after redesign.



(A)



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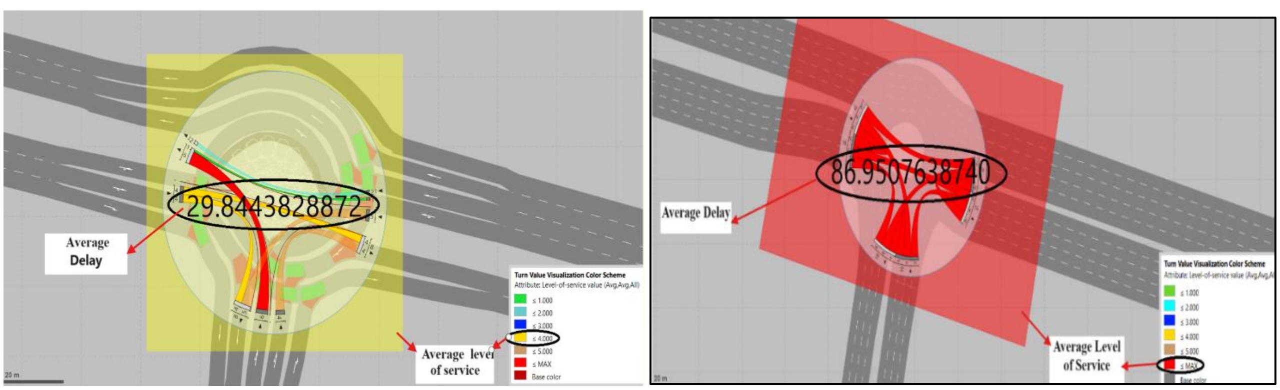

(C)

Figure 13. Average delay and the average level of service for A) Al-Tarbia roundabout, B) Saeed Al Asar roundabout, and C) Al Mohafada's roundabout versus the alternative turbo roundabout.

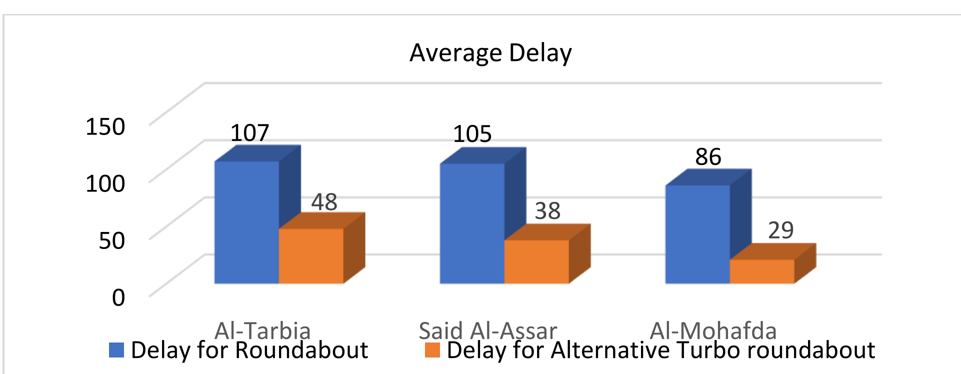

Figure 14. Average vehicle delay: comparison between conventional and turbo roundabouts in three roundabouts.

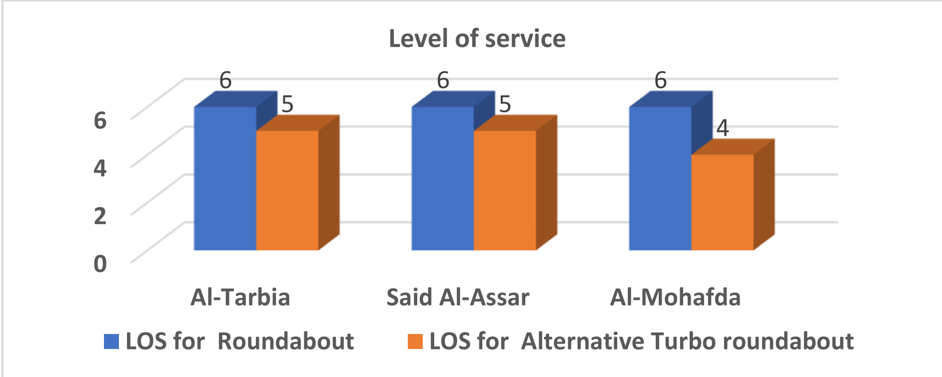

Figure 15. Average level of service: comparison between conventional and turbo roundabouts in three roundabouts

These figures show a significant decrease in delay across all approaches. This leads to improved operational performance at the intersection. Therefore, LOS across all approaches showed greater improvement per movement at the roundabouts. At the Al-Mohafda roundabout, the level of service changed from LOS F to LOS D, resulting in a 66% reduction in vehicle delays. As well as being altered from LOS F to LOS E for Al-Tarbia and Said Al-Assar, resulting in 55% and 63% reductions in vehicle delays, respectively. As a result, previous studies [15], [39] predicted that the proposed designs would improve LOS overall compared to the traditional design. The turbo roundabout achieved satisfactory results compared to the current multiple roundabouts, which are considered prohibited due to the curved lane dividers that guide drivers to the appropriate lane they chose before entering the roundabout.

4. Conclusions

The paper used a turbo roundabout as an alternative to the conventional three-roundabout system with a multi-lane roundabout in Karbala city. The turbo roundabout design has reduced vehicle delays and improved overall performance metrics for all three roundabouts. At the Al-Mohafda roundabout, the delay was reduced by 66%. The level of service changed from LOS F to LOS D. Also, Al-Tarbia and Saeed Al-Asar roundabouts reduced delay by 55% and 63%, respectively. Turbo roundabouts show significant advantages over multi-roundabouts in terms of safety performance. The increase in the TTC value has reached 41% at the Al-Tarbia and Al Mohafada roundabouts, while at the Saeed Al-Asar roundabout, the price is 33%. Turbo roundabouts have fewer conflicts than standard roundabouts and help drivers emerge with fewer conflict points; in Al-Tarbia, Saeed Al Asar, and Al Mohafada, the percentage change in favor of the turbo roundabouts of 69%, 74%, and 85%, respectively. A turbo roundabout could be an alternative to traditional multi-lane roads in Iraq, given the aggressive driving behavior there. Future work integrating the turbo roundabout with the traffic signal at the Al-Tarbia roundabout to manage violations of priority rules and investigate the impact of these signals. Also, looking at smaller species to see if traffic lights improve their capabilities. If larger species do not benefit from traffic signals, smaller species are probably not worth considering.

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Conflict of interest

The authors declare that there is no conflict of interest.

Author Contribution statement

Noor Jabbar Jihad proposed the problem statement. Hussein Ali Ewadh, Raid R.A. Almuhanna, and Noor Jabbar Jihad equally conducted and revised the work and provided a scientific database.

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