Transit signal priority strategies applied in roundabouts to reduce conflicts and vehicular travel times

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Abstract— ***In the last 20 years, the use of roundabouts has become widespread worldwide. This is due to the advantages they offer over other types of intersections, such as their ability to achieve a continuous vehicular flow and provide greater road safety for drivers and pedestrians. However, when a roundabout is not working properly, its operational capacity is exceeded. In this scenario, increases in directional vehicular conflicts and in travel time are observed, which directly affects the users of the road system. These problems are mainly generated by lane changes and queuing vehicular flow that can block some roundabout accesses. In Peru, most of the roundabouts that present this type of problem have not been designed to meet the exponential growth of the vehicle fleet in recent years, leading to congestion and delays because of inadequate road planning. For this reason, the existence of roundabouts that exceed their capacity is a latent reality that is not only present in Peru, but throughout Latin America. Given this problem, the application of transit signal priority strategies is proposed to reduce vehicular conflicts and travel times. For the present investigation, a traffic light roundabout located in a commercial area of the city of Lima was selected as a case study. It is characterized by having many heavy vehicles and being part of the route of a Bus Rapid Transit (BRT) transportation system. The effectiveness of the proposal was validated using Vissim software. The results obtained demonstrate the influence of traffic light priority strategies reducing conflicts by 15% and vehicular travel times by 29%.***

Palabras claves—***Roundabouts, traffic lights, vehicular conflicts, travel times, microsimulation, Vissim.***

I. INTRODUCTION

The use of roundabouts has shown multiple benefits compared to other intersections. These include safety, aesthetics, and lower maintenance and operating costs [1]. However, a roundabout that does not work properly, due to a poor geometric design, an excess of traffic intensity, or an unbalanced distribution between its entrances, generates inefficient traffic self-regulation, which leads to congestion problems, an increase in travel time, and a greater number of vehicular conflicts [2]. One factor contributing to vehicular congestion is the heavy traffic of heavy vehicles. This is due to their large size, which generates sudden turns in their movement and obstruction to other vehicles within the roundabout. Another factor is the lack of priority for public transport buses, which negatively affects the travel time of these vehicles, despite providing a service that benefits many people.

The application of transit signal priority strategies is one of the most viable options to deal with this problem. This is because transit signal priority allows giving preference to certain vehicles at intersections regulated by traffic lights. In the case of roundabouts with exceeded maximum capacity that resort to the use of traffic lights, their use would allow giving priority to the vehicle that generates the greatest problems within the intersection, thus reducing vehicular conflicts and root travel times, since that would avoid major obstructions and long queues inside roundabouts [3].

One of the roundabouts where this problem is evident in Lima is the “Plaza Ramón Castilla” roundabout. This is because it is considered a roundabout with congestion problems during its hour of maximum demand. A representative feature is its way of regulating traffic through traffic lights, which is not adapted to the needs of vehicles. This causes the vehicular flow to be trapped in large queues, which causes conflict points at the entrances and consequently, longer travel times. The problem is also increased by the high demand for heavy vehicles passing through the roundabout. Their large size does not allow them to move normally on curved sections, which generates directional conflicts [4], which harms light vehicles who choose to perform lane change maneuvers to continue their route, increasing the delay of the system.

On the other hand, this roundabout is characterized by the passage of BRT buses, which do not have priority of passage. In other words, there is no adequate traffic light cycle that adapts to the needs of the public transport system. In this way, not only the movement of the buses is affected, but also the movement of the entire vehicle fleet. This directly affects the travel time of the road system due to the low capacity of the roundabout even with a traffic light system.

This research seeks to analyze the influence of the use of transit signal priority strategies and their relationship in reducing vehicular conflicts and travel times at roundabouts. For this reason, a comparative analysis will be carried out between the application of a passive transit signal priority and an active transit signal priority as transit signal priority strategies.

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II. STATE OF THE ART

Faced with this problem, different investigations have studied the implementation of transit signal priority at intersections that have the passage of public transport [5]. Within these systems are passive, active, and adaptive systems. Furthermore, passive transit signal priority systems are based on fixed-time controls, while active strategies work through detectors located near intersections. On the other hand, adaptive systems are characterized by considering both public transport and private transport through detectors [6].

In an investigation carried out in Taichung, the influence of the Transit Signal Priority (TSP) of the BRT line is analyzed. The authors seek to reduce BRT delays at intersections. In this way, the study combines the theory of low-cost Classic Transit Signal Priority (CTSP) with the principle of integrated benefits of intersections, thus creating Crossway Considered Transit Signal Priority (CCTSP). This method adds vehicle detection, timing prediction, and strategy decision algorithms, thus eliminating the drawbacks of using CSTP [7].

Another study carried out in China presents a three-part approach, in which it proposes a bus priority control logic with overlapping phases, a multiphase control algorithm for bus signal priority, and passenger delay estimation. This proposal seeks to reduce the problems detected initially at the intersection. The results obtained were the optimization of passenger delays [8].

A signalized intersection actuated by vehicle (VA) is one where there are detectors in the traffic lanes, which detect the arrival of vehicles. This information is used by the signal controller to calculate the optimal phase times. The study that took as a case study the signalized intersection located in West Lafayette; Indiana developed a microsimulation model using the Slam II software. The work carried out describes the characteristics of actuated control that offer advantages over fixed-time signaling. Finally, it was possible to conclude that, for some scenarios, the improved strategies reduce vehicle delay by more than 30% [9].

Another investigation proposes a probabilistic model with 2 loop detectors, which are placed in the subsoil of the intersection. A new modeling approach to estimate traffic light queue and phase times was presented. The results of the probabilistic approach were compared with the results of repeated microscopic simulations, showing a good result. Finally, it was concluded that the model provides an estimation of the uncertainty of the queues and the configuration of the traffic light signal, calculating the evolution of its probability distribution [10].

Similarly, a study conducted to optimize the maximum capacity of vehicles passing through a signalized intersection while the green light is activated applied a cooperative adaptive cruise control (CACC) system. In this investigation, a platoon of 16 vehicles was simulated to obtain synchronized vehicle movements that facilitate the reduction of travel times of vehicles passing through the intersection. The simulation results demonstrate that using the proposed method, the ability to maintain urban arteries could be increased considering that vehicles can maintain a small safe distance between them [11].

III. METHODOLOGY

The methodology used in this research is divided into the following stages, as detailed in Fig. 1.

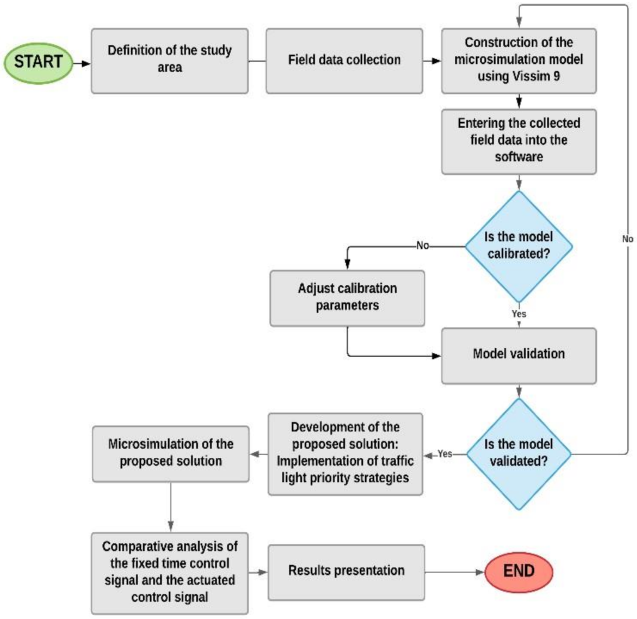

Fig. 1 Stages of the investigation process.

A. *Definition of the study area*

Before data collection, vehicular trajectories within the roundabout were identified. For this, a reconnaissance of the study area was carried out to know the vehicular behavior during the hour of maximum demand. In total, 5 accesses with 28 vehicular trajectories were identified.

B. *Field data collection*

Data collection is carried out in the field, considering the geometry of the intersection, the traffic light cycles present, and the vehicle count during the hour of maximum demand, whose methodology was to record 4 hours of video with a drone in 2 representative days. Vehicle capacity will be determined by the type of vehicle (linear motorcycle, car, minibus, bus, truck, trailer, and Metropolitan BRT) and pedestrian (children, adults, elderly). In this way, the vehicular flow was identified in the accesses and in the existing paths as reflected in Fig. 2.

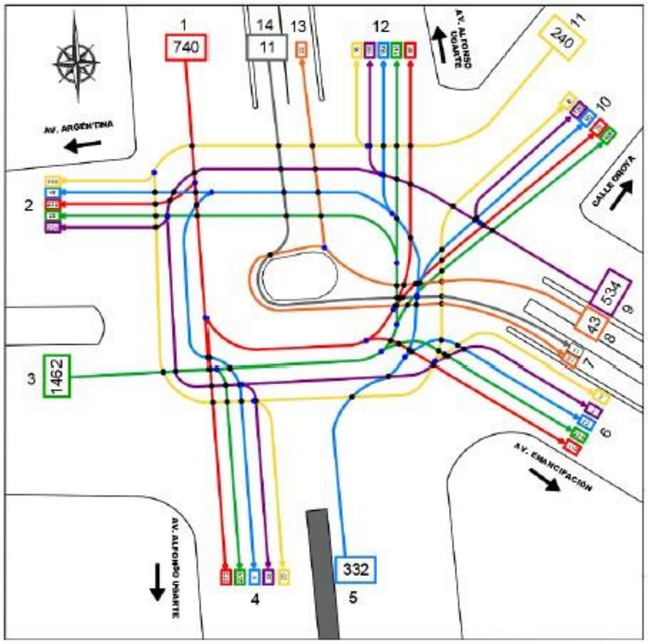

Fig. 2 Roundabout vehicular flowchart.

In addition, tables were made for each OD matrix by type of vehicle (linear motorcycle, car, minibus, bus, truck, trailer, and Metropolitan BRT) to stratify the input data that was introduced during the development of the current situation in Vissim program. In this way, all the necessary data was obtained to recognize the different problems that are generated within the roundabout for later analysis. Table I shows the OD matrix by type of vehicle - automobile of the vehicle capacity carried out in the study case during the hour of maximum demand of the first representative date.

TABLE I

MATRIX ORIGIN-DESTINATION BY TYPE OF VEHICLE-AUTOMOBILE

Destination Origin	2	4	6	10	12	Total
1	130	182	60	50	20	442
3	2	126	184	332	308	952
5	36	4	18	62	68	188
9	172	30	2	84	142	430
11	128	14	2	4	10	158
Total	468	356	266	532	548	2170

Likewise, the existence of 8 critical trajectories within the roundabout was determined and the free flow speeds by type of vehicle were calculated. For this, the travel time of 15 vehicles in each critical trajectory was measured. Next, Table II is presented the data obtained from the travel time of each critical trajectory.

TABLE II

VEHICULAR TRAVEL TIMES OF CRITICAL TRAJECTORIES

	Critical trajectories							
No	1-6	3-12	5-12	9-2	11-2	8-7	8-13	14-7
1	190.8	147.8	150.6	60.4	70.5	108.3	112.2	81.3
2	287.3	219.5	163.1	78.3	71.4	108.4	42.2	44.1
3	144.5	194.3	172.9	60.5	67.1	79.6	27.6	47.2
4	253.8	206.3	145.7	54.4	51.3	61.7	20.8	75.3
5	230.3	203.5	173.1	58.5	95.4	130.1	125.2	44.1
6	166.8	201.0	152.9	117.9	57.3	95.0	107.0	81.3
7	287.3	203.6	155.3	155.1	86.1	165.8	34.6	88.0
8	230.3	169.3	169.4	112.6	24.1	148.2	30.4	135.7
9	175.1	172.4	169.3	110.9	31.6	133.8	37.1	50.5
10	182.0	162.2	145.3	105.2	23.7	116.4	22.1	46.1
11	177.5	160.6	132.5	99.9	25.9	130.3	34.2	81.3
12	231.7	167.4	162.3	89.2	68.4	125.3	69.5	47.2
13	192.2	172.2	171.3	63.7	57.3	119.3	49.6	47.2
14	226.3	156.0	130.3	65.8	63.8	145.4	76.3	75.3
15	231.7	241.0	128.3	54.2	46.3	119.3	50.4	44.1
Prom.	213.8	185.1	154.8	85.8	56.0	119.1	55.9	65.9

Finally, the calculation of the free flow speed by type of vehicle was carried out to be able to assign these values in the simulation model of the current situation in the Vissim software. For this, the travel times of 210 vehicles were determined, 30 for each type of vehicle, over a representative distance of 30 m depending on the type of vehicle (Fig. 3).

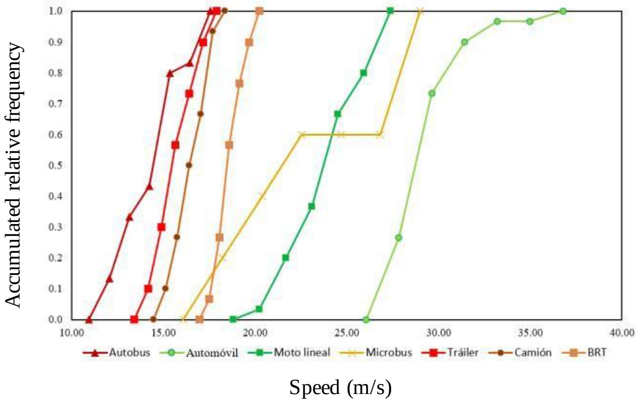

Fig. 3 Accumulated relative frequency of speeds in free flow.

C. *Construction of the microsimulation model*

After the compilation of vehicular and pedestrian flows, geometry, and fixed traffic light times, the model of the current situation was developed in the Vissim software. For the correct representation of the model, the speeds of the vehicles, vehicle typology, flows, geometric data, cycles of the fixed traffic light, passing priorities and the parameters of the driver's behavior were configured (Wiedemann 74). Fig. 4 shows the model of the current situation of the roundabout.

Fig. 4 3D microsimulation view of the "Plaza Ramón Castilla" roundabout.

D. *Calibration and validation of the current situation*

The model calibration process aims to accurately represent the reality of the roundabout. For this, the minimum number of runs is evaluated, and it is extended that a minimum of 15 runs is needed to correctly represent the scenario. The Wiedemann 74 parameters (ax=0.5, bxadd=1.1 and bxmult=3) were adjusted with a heating time of 600 seconds and a total simulation time of 4200 seconds as recommended by the Federal Highway Administration (FHWA). On the other hand, the critical routes were selected and the travel time of 15 vehicles was counted according to the video material. Table III shows the comparison of the travel times analyzed in the field vs. the microsimulation model.

TABLE III
FIELD TRAVEL TIMES VS MODEL

No	1 - 6				5 - 12		9 - 2	
	Field	Model	Field	Model	Field	Model	Field	Model
1	190.84	234.20	147.83	176.53	150.55	146.61	60.38	83.3
2	287.27	268.72	219.48	179.16	163.08	135.17	78.26	82.0
3	144.50	246.68	194.27	185.92	172.93	148.84	60.47	77.3
4	253.76	250.38	206.33	179.97	145.74	140.68	54.39	75.4
5	230.33	224.43	203.51	183.36	173.08	158.27	58.47	83.7
6	166.80	215.08	200.96	188.79	152.93	148.89	117.90	84.8
7	287.27	194.87	203.55	183.08	155.26	137.63	115.07	83.8
8	230.33	203.16	169.25	172.14	169.37	145.71	112.61	72.9
9	175.09	244.46	172.36	192.36	169.32	180.42	110.87	76.1
10	182.02	215.77	162.18	171.56	145.26	138.67	105.17	74.7
11	177.46	188.71	160.58	179.73	132.54	151.44	99.90	84.4
12	231.73	218.73	167.36	170.86	162.25	160.70	89.24	77.1
13	192.15	254.51	172.16	185.17	171.25	154.84	63.70	78.3
14	226.28	236.25	156.00	160.39	130.28	162.11	82	78.24
15	231.73	212.81	240.98	184.63	128.32	157.92	16	82.05

Finally, the calibration test was performed for each critical path using the null hypothesis Randomization Test program at a confidence level of 95%, where it was obtained that the model is calibrated. In Fig. 5, the Randomization Test for trajectory 8 – 13 is shown, with a mean difference value of 0.73.

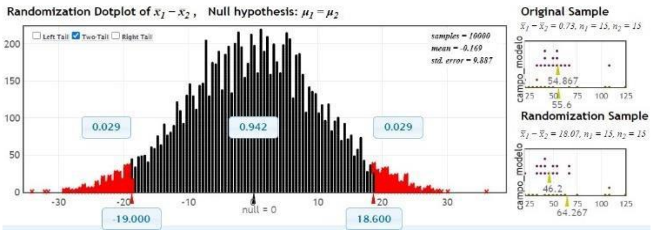

Fig. 5 Randomization Test for trajectory 8-13.

For the validation of the model, data from a second sample was used, to validate the dynamic behavior of the microsimulation model. The model was run 15 times and a second randomization test was performed at a confidence level of 95% for each critical path, where the model was validated. In Fig. 6, the Randomization Test for path 3-12 is shown, with a mean difference value of 0.22.

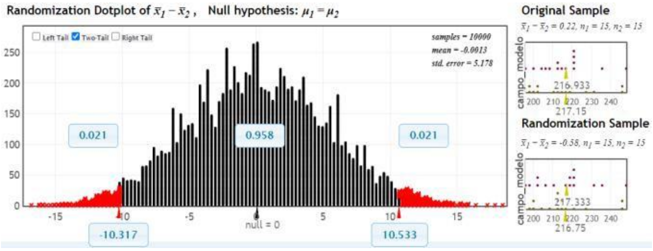

Fig. 6 Randomization Test for trajectory 3-12

E. *Approach of the proposed solution*

As a solution to the problems of the roundabout, the application of two types of transit signal priority strategies is proposed, the first uses a fixed system and the second uses an actuated system. This is to analyze from both approaches the influence of transit signal priority strategies in reducing conflicts and vehicular travel times.

In the case of the fixed transit signal priority system, the data from the model of the current situation was used as a basis, because the roundabout had this type of transit signal priority system from the beginning. However, despite this, it was not enough for the roundabout to function properly since the passage of the Metropolitan BRT buses is very irregular throughout the hour of maximum demand.

On the other hand, for the application of the actuated traffic light system, detectors were placed in each trajectory where the BRT vehicles cross, as shown in Fig. 7. With this improvement, the BRTs are given priority to pass through the detectors, generating a constant flow inside the roundabout.

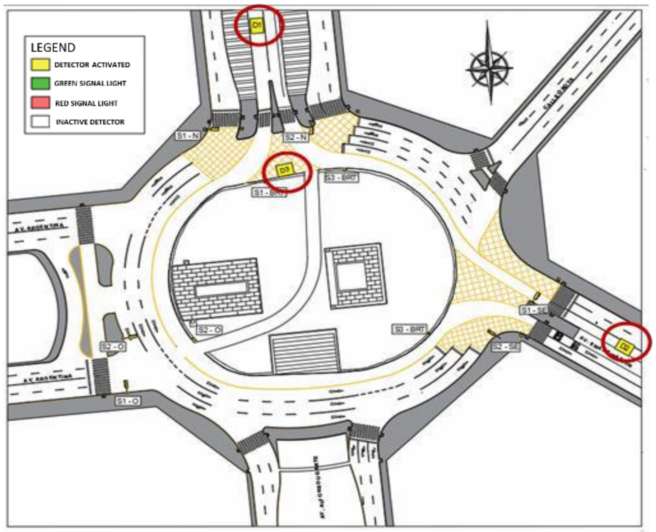

Fig. 7 Location of detectors within the roundabout

Subsequently, the design diagram of the transit signal priority system was made using the Visvap tool. Fig. 8 shows the operation of the transit signal priority system when a vehicle is detected by detector 1.

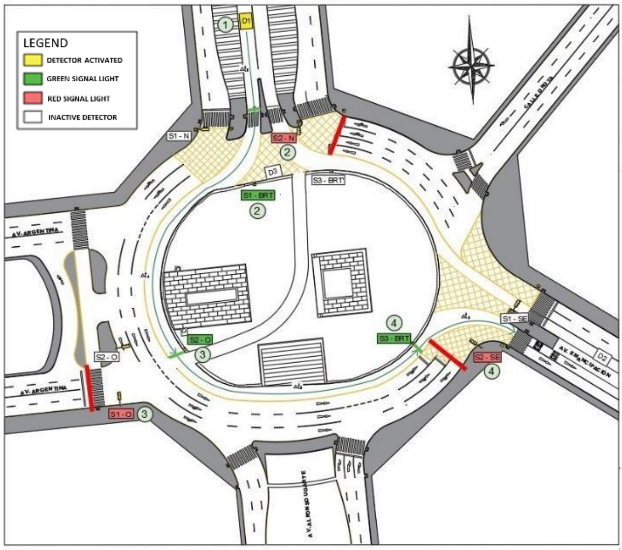

Fig. 8 Scenario for detector #1.

Finally, the number of vehicular conflicts and travel times in the critical trajectories of the roundabout were analyzed. With these indicators, it is possible to evaluate and compare the results obtained when applying a fixed transit signal system and an actuated transit signal system in roundabouts that have already exceeded their maximum capacity.

IV. RESULTS

The contribution of this research is aimed at the need to understand and analyze the influence of the use of transit signal priority strategies in reducing vehicular conflicts and vehicular travel times at roundabouts. Mainly in those roundabouts that have seen their maximum capacity exceeded, so they are forced to control their traffic through control devices such as traffic lights.

After applying the transit signal priority system in the case study, a Randomization Test was performed with 10,000 samples, applying the Right Tail test with 95% reliability as shown in Fig. 9. This is to verify which transit signal priority strategy provided statistically has shorter roundabout travel times.

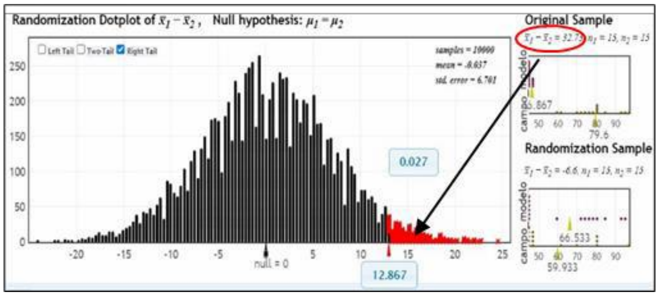

Fig. 9 Null hypothesis test of the travel times of both traffic light priority strategies on trajectory 14-7.

Likewise, with the travel times defined for both traffic light priority strategies, both data are compared in each of the critical trajectories. Table IV shows the travel time data obtained.

TABLE IV
TRAVEL TIMES FOR EACH CRITICAL TRAJECTORY

Trajectory	Traffic light type	Travel times	Reduction percentage
1 - 6	Passive Active	227.25 184.57	19%
3 - 12	Passive Active	179.60 140.44	22%
5 - 12	Passive Active	151.19 104.99	31%
9 - 2	Passive Active	79.64 69.71	12%
11 - 2	Passive Active	53.56 49.82	7%
14 - 7	Passive Active	80.13 47.23	41%
8 - 13	Passive Active	55.39 25.16	55%
8 - 7	Passive Active	120.65 67.91	44%

In Fig. 10, the behavior of the travel times of the critical path 11-7 is observed using both traffic light priority strategies within the roundabout under study.

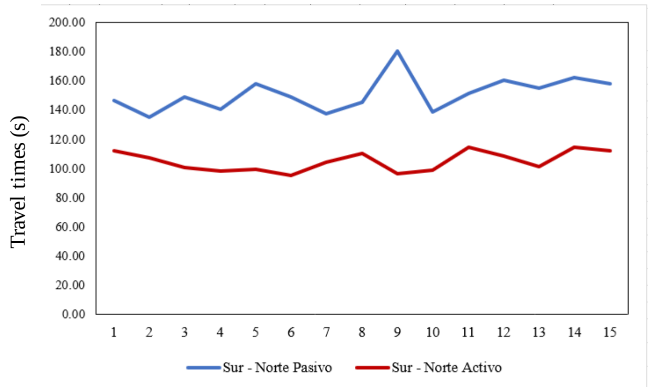

Fig. 10 Comparative graph of travel times for trajectory.

As can be seen in the graphs above, the travel time is much shorter using an active transit signal priority system than using a passive transit signal priority system. Concluding, better results are obtained in the trajectories where the BRT travels because it is given traffic light priority. In this sense, a greater reduction in travel times is observed on trajectory 11-7, exclusively for BRT, than on routes 5-12.

After analyzing the influence of these strategies in reducing travel times at the roundabout, we proceed to compare the results obtained concerning vehicular conflicts. For this, the SSAM program was used, which is a Vissim complement, whose purpose is to count the conflict points generated in each model run. As can be seen in Table IV, the number of vehicular conflicts has decreased by 15% using an active transit signal system compared to a passive transit signal system.

TABLE V

NUMBER OF VEHICULAR CONFLICTS USING TWO TYPES OF TRANSIT SIGNAL PRIORITY STRATEGIES

	Fixed transit signal system	Actuated transit signal system
Number of vehicular conflicts	2250	1920

V. CONCLUSIONS

In the results of table IV, the critical values of travel times in trajectories 1-6 and 3-12 can be identified, reaching an average of 227.25 and 179.58 seconds, respectively. After applying the actuated transit signal system, it was possible to observe how the average travel times of these routes decreased by 19% and 22%. It can be concluded that the applied active transit signal priority strategy is efficient in reducing travel times at roundabouts that have exceeded their capacity.

On the other hand, it is observed that, on average, the travel time of the roundabout has been reduced by 29% using an active transit signal priority strategy compared to the use of a passive transit signal priority strategy. It should be noted that the critical trajectories that obtained the best results were those where passage priority was assigned to the BRT system.

Table V shows the total number of vehicular conflicts present at the 2250 roundabout when a fixed-time transit signal system is used, while when using an actuated transit signal system this number decreases to 1920. In this sense, we can say that, if we compare both quantities of vehicular conflicts, the use of an actuated transit signal system reduces vehicular conflicts by 15% more than the use of a fixed transit signal system.

The traffic light priority proposal that is best adapted to the conditions of the roundabout is the implementation of an actuated transit signal system. The use of the Visvap program was chosen for the programming of the detectors and traffic lights within the roundabout. Finally, the microsimulation of the proposal was carried out and a better displacement of both the BRT buses and the vehicles, in general, was obtained.

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