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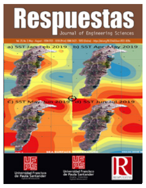

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Alternatives to improve operational traffic in roundabouts using microsimulation

Alternativas de mejoramiento operacional de la movilidad en glorietas usando microsimulación

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ABSTRACT

Keywords:

Intersection, roundabout, turbo-roundabout, signalized intersection, overpass, traffic, stochastic tracking model, micro simulation, VISSIM.

Roundabout in urban arterials is likely to block roads or generate long queues of vehicles due to the constant changes in urban dynamics near to the interception. Several alternatives to modify the flow pattern or geometry and infrastructure need to study previously to propose a final design solution for a roundabout with traffic issues. In this study, a review of three alternatives to improve the operational traffic are discussed; signalized intersection, turbo-roundabouts, and overpass/underpass. Also, the application of these alternatives is evaluated in a "classic" roundabout located at Tunja city that has a maximum of 3691 Veh/h counted, and it is operated in a saturated condition. Micro simulation is used from a calibrated model with volume counted, vehicle composition, and speeds in the VISSIM software. Results show that signalize the roundabout does not improve the operational traffic (with a reduction of 38% of approach speed) and, the turbo-roundabouts are a mid-term solution that meets the traffic demand on 15 years with a progressive loss of service (with a mean approach speed of 6.4 Km/h at 15 years). The constructions of underpass and overpass show to be the only solution that increases four times the travel speed throw the roundabout and keep the acceptable speed at the end of cyclic live of intersection (18.7 Km/h at 20 years).

RESUMEN

Palabras clave:

Intersección, glorieta, turbo-roundabout, intersección semaforizada, paso a desnivel, tráfico vehicular, modelo de seguimiento estocástico, microsimulación, VISSIM.

En las intersecciones tipo glorieta ubicadas en vías arteriales es altamente probable que se presenten bloqueos o largas colas de vehículos debido a la evolución de la dinámica urbana. Existe una variedad de alternativas de modificación tanto del patrón de flujo como de la geometría e infraestructura que requieren ser estudiadas para la presentación de la solución vial definitiva. En este estudio se realiza una revisión de literatura de tres alternativas para la mejora de la movilidad de las glorietas; semaforización, turbo-roundabouts y pasos a desnivel. Posteriormente, se evalúa la factibilidad de las alternativas para una glorieta "clásica" ubicada en la Ciudad de Tunja (Colombia), donde se aforó un máximo de 3691 Veh/h y que opera por encima de su capacidad. La investigación se realiza usando microsimulación de un modelo calibrado en el software VISSIM con datos aforados de volúmenes, composición vehicular y velocidades. Los resultados muestran que la instalación de semáforos afecta la condición de operacional de la glorieta (con una reducción en un 38% de la velocidad de entrada) y, las turbo-roundabouts pueden ser una solución que se ajustan a la demanda (volumen de tráfico) hasta por un periodo de 15 años con una reducción gradual en la calidad de servicio (con velocidad de entrada promedio de 6.4 Km/h en 15 años). La solución permanente a la movilidad requiere pasos a desnivel que aumentan cerca de 4 veces la velocidad de circulación actual en la glorieta y permite velocidades aceptables de circulación (18.7 Km/h en 20 años).

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Introduction

Traffic congestion in urban spaces is one of the biggest problems facing sustainable development today [1]. One of the areas with the highest congestion is generated at points where roads with high vehicular traffic converge known as intersections. On the other hand, roundabouts have proven to be a safe intersection alternative for both motorized vehicles and pedestrians [2], however, they require compliance with operational requirements, capacity, traffic organization, and development of surrounding areas. [3]. Some of the solutions proposed for this problem is the implementation of traffic lights in all branches [4] or in some of them [5], the construction of turbo-roundabouts as a common alternative for multi-lane roundabouts [6] or the articulation with elevated and / or depressed steps.

Regarding advances in the subject, it has been found that when the capacity of the roundabout is reached, the signalized intersection presents a better performance [4]. Single-branch traffic lights allow the best performance of the roundabout when this branch contributes more than 40% of the total traffic volume, and in such cases, delays, stops, arrival times and problems can be reduced by up to 60% travel times [7][5]. The introduction of turbo-roundabouts may offer security benefits both in terms of service level, as well as in the values of collision time and invasion time [8]. Studies have shown significant reductions in saturation [9], delay times, travel times [7], and improvements in service level [10] at intersections that implement elevated or depressed crossings.

However, the traffic lights of a roundabout is a solution to the immediate problem and are not viable as the number of vehicles increases [5], being a temporary alternative [9]. In the case of turbo-roundabouts, the guidelines are still being studied [6] and when comparing the designs in different countries, modern and elliptical roundabouts present a greater capacity. [11]. According to the above, there is still no consensus on the alternative that can be more efficient to improve the performance of existing roundabouts. Also, with the help of micro simulations, it is possible to obtain valuable information regarding the changes in the flow pattern due to the changes in traffic and / or in the infrastructure that are desired [12].

The article focuses on the study of traffic improvements in the "Glorieta Norte" of the city of Tunja due to its importance, taking into account the methodological steps of the design of intercessions of the Highway Design Manual [13] in section 6.2, knowing the current capacity of the intersection, volumes, vehicle composition, and routes that are made in the intersection. These data were used to model and calibrate the current situation using the VISSIM program. Subsequently, the alternatives for modifying the intercession such as traffic lights, turbo-roundabout, and overpasses are presented and the comparison of the results of the simulation of said scenarios, analyzing each of the cases.

Roundabout modeling

Different types of computational tools have been used for the modeling of roundabouts using deterministic models of analytical or empirical type of stochastic simulation models. [14][15]. One of the software based on stochastic tracking models and dynamic speeds that are used to perform the simulations is VISSIM (Verkehr In Städten - SIMulation) for its acronym in German [16]. This software presents a high-quality visual interface, allowing the observation of traffic behavior in different scenarios including roundabouts [4], and geometric, traffic, and behavior characteristics that have been evaluated [13]. In this way, it allows simulating the behavior of each vehicle within the network [12].

Several studies of the successful application of VISSIM have been reported. A traffic optimization study was conducted at the intersection near the Songjiang University Town public transport station, where it included both vehicles and pedestrians in the model and made adjustments to traffic light control, straight lanes, and left turn. [17]. In another investigation, VISSIM was used to evaluate through micro simulations the reduction of the impact on the performance of the construction of the depressed in "Patal Pusri" in the city of Palembang [12]. VISSIM has also undergone validation processes to measure its performance at vehicular intersections. [18]. This software also allows entering and calibrating the approach speed, reduced speed zones, circulating speed, priority rules, traffic allocation and, considers the driver's behavior through a rules-based psycho-physical monitoring model for lateral movements [19][20].

Roundabout traffic lights

Roundabouts have been successfully used in the world

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together with traffic control systems [21], the traffic light of a roundabout is useful as a treatment especially during peak hours [5]. It favors the reduction in travel times, congestion, and accidents [5] [22], allowing a balanced flow, giving priority to pedestrians and public transport [23] and, it is cheaper than other types of measures for roundabouts [24].

In several locations in the United States, an analysis of the traffic light intercessions of different roundabouts was carried out, where they determined that they present better performances in the delay time when the roundabout capacity is reached. [4]. In the city of Baghdad, the operation offered by roundabouts in traffic management determined that, if one of the branches contributes more than 40% of the traffic volume, the traffic light of this single branch allows the best performance of the roundabout [7]. In this sense, another author determined, using a partial traffic light of the roundabout, the problems of delays, stops, arrival times, and travel times can be reduced by up to 60% [5]. However, this study and others have shown that the signaling of this type of intercession is only a temporary alternative. [9].

Turbo-roundabouts

Turbo-roundabouts are characterized by the turbine shape that the central island takes due to the offset of one of its lanes, causing the main flows of the intersection to give way only to vehicles that circulate on one lane of the ring of the intersection [25][26]. These have more than one lane on the turning road and the selection of the lane for the route must be made before entering the intersection [25], in this way the traffic flows advance separately at the exit of the roundabout [26]. This type of intersection has been studied in countries such as the Netherlands, Germany, South Africa, Italy, Spain, and Belgium [27].

Due to this, modern and elliptical roundabouts have greater capacity, considering or not the traffic light [6] [11]. Turbo-roundabouts can offer security benefits both in terms of service level and collision time values such as invasion time [8]. The presence of separate lanes within turbo-roundabouts in Poland found that lane separation generates a speed reduction, causing the need for safety performance functions. [3].

Overpasses

One of the ways to solve the problem of road congestion caused by intersections is the use of elevated and / or depressed crossings on the main streets [9] [12] [28]. In this sense, studies have presented the advantages of providing this type of solution as an alternative to improve an intercession with a poor level of service in the city of Makassar (Indonesia) [9] and in the tourist province of Bali (Indonesia) [10]. On the other hand, mobility studies in the city of Chicago have shown that the definitive solution in intercessions requires both an elevated and depressed crossing [29], however, the use of depressed or elevated passages has been shown to reduce travel times in roundabouts located in Baghdad [7].

Methodology

The urban expansion that the city of Tunja has presented in recent years has generated an increase in vehicular flow through the sector known as "La Glorieta" to the north of the city and the deterioration of mobility in this area. This intersection 4 national roads that connect the departments of Boyacá, Cundinamarca, and Santander through a circulation ring with an internal and external diameter of 54 and 70 m respectively, built in the 60s and, in its initial design, it was not taken into account the inclusion of pedestrians and cyclists as a traffic actor [30][31].

As a design procedure for the roundabout update, the Road Design Manual [13] in section 6.2 is followed. To examine the pre-feasibility of this type of solution in Colombia, we start with the elements outlined in Chapter 7 of the Road Signaling Manual. [32] For the turbo-roundabout design proposal of this study, the procedure compiled by [25] [33] was followed. The design of the overpass begins with the basic intercession schemes and the basic design criteria found in sections 6.3.2.1 and 6.3.2.2 of the Highway Design Manual [13] respectively.

Different alternatives were modeled such as intersection traffic lights, Turbo-roundabouts, and elevated and depressed crossing, preserving the existing level crossing. These simulations are carried out in the VISSIM software due to the benefits previously indicated. To evaluate future scenarios, a 5, 10, 15, and 20-year projection was made with an annual growth rate of 1.53% in the volume of traffic, thus complying with the provisions of section

6.2.3 of the INVIAS Manual [13].

La Glorieta Norte is located at the height of Calle 35 and Cra 6, where Av. Oriental, Avenida Norte, La Dg 38, or Exit to Bucaramanga, Cl 35, or Av. Villa Olímpica, and Av. Maldonado, according to [31], is considered the urban epicenter of the city, dividing the urban perimeter into East, West, North, and South, and has 2 lanes at each entrance and exit (see Figure 1).

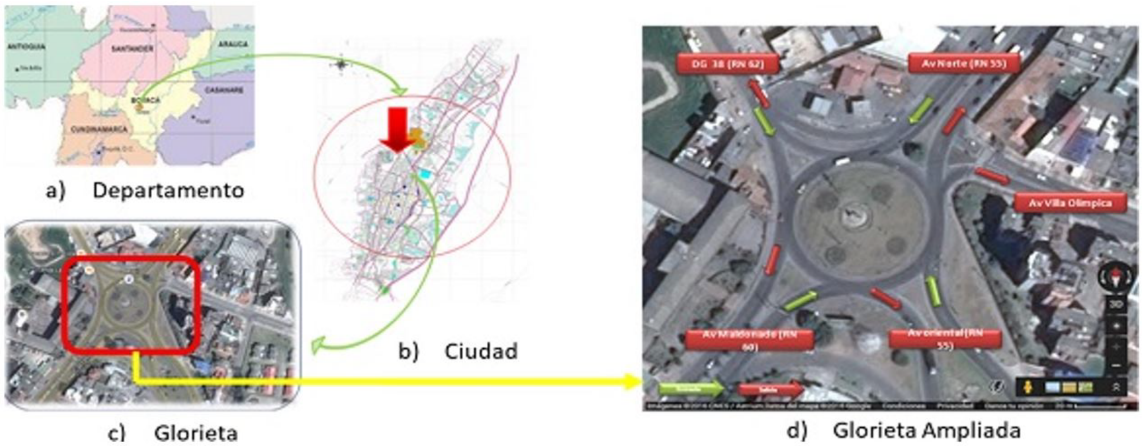

Figure 1. Location of the study area.
Source: images a) and b) taken from Wikipedia and images c) and d) from GoogleMaps

Study and characterization of the traffic

A manual gauging by direct counting was used, for which, the equipment was used; Robotic IP video camera and application developed with the CyberTracker program [34], see Figure 2, for vehicle counting from the videos taken and computers with a video format player .h256.

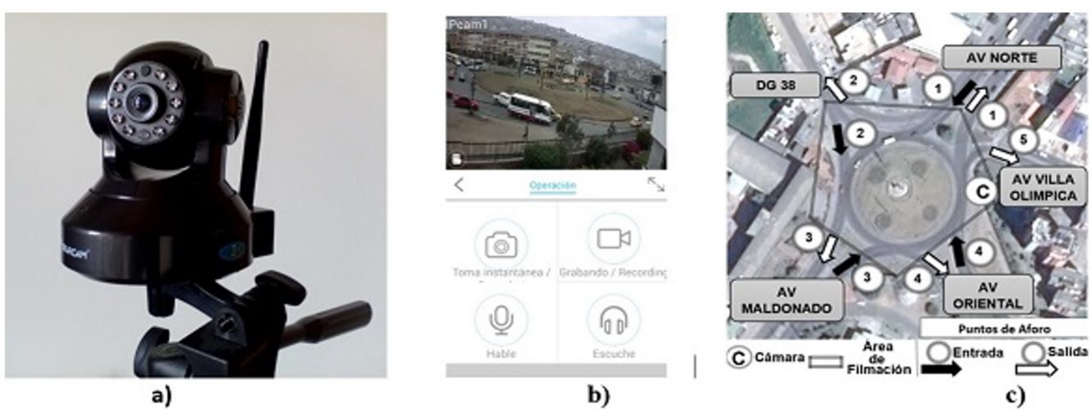

Figure 2. a) IP Surveillance Camera, b) Camera Monitoring through Smartphone, c) Location of the Capacity Points.
Source: Images a) and b) own source and image c) adapted from Google Maps

The information was taken with the camera located in the "El Recreo" condominium from the gauging points indicated in Figure 2-c, in total 4 entrances and 5 exits of the intersection were gauged. Initially, the gauges were carried out at the intersection entrances to determine the hour of maximum demand (HMD) during Tuesday, from 5:30 am to 10:00 pm (67 videos of 15 minutes) corresponding to one-day typical circulation. Subsequently, the capacity of the departures was made only for this time.

Figure 3 shows the hourly distribution of the volumes registered during the day, the hour of greatest demand is between 5:30 pm and 6:30 pm, with a total of 3691 Vehicles / h. It is observed that the highest percentage of vehicles that circulate through it are for the private use of a light type, followed by individual public transport such as taxi, and in third place, urban collective public transport; These three categories represent three-quarters of the traffic in the sector.

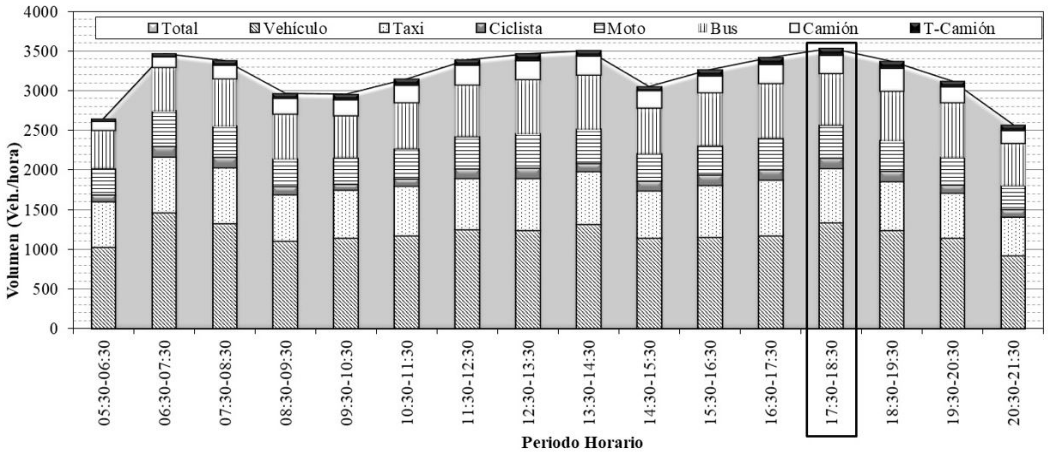

Figure 3. 2016 Vehicle Volumes (peak demand time indicated in the box).

Figure 4 shows the percentage of vehicles that enter the intersection, being the Access of Av. Norte (entrance 1), the one that contributes the most traffic to it, followed by Av. Oriental (entrance 4) and Av. Maldonado (entrance 3) and finally Dg. 38 o Av. Bucaramanga (entrance 2). In the same Figure 4, it can be seen that Av. Norte (exit 1) and Av. Maldonado (exit 3) are the exits with the highest demand, followed by Av. Oriental (exit 4) and Av. Villa Olímpica (exit 5), and lastly Av. Route to Bucaramanga (exit 2).

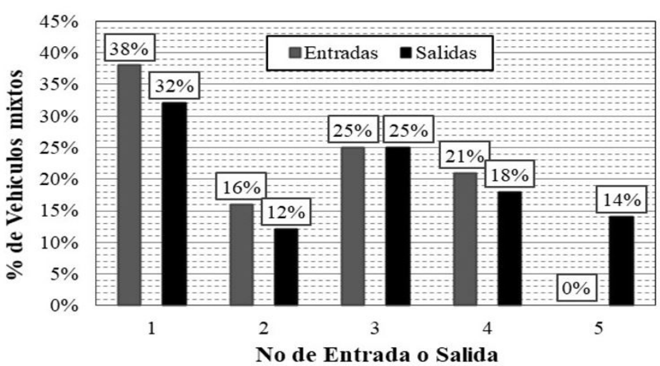

Figure 4. Distribution of traffic by accesses to the roundabout.

The capacity of a roundabout per hour is calculated using the expression proposed by Wardrop, equation (1) [35]:

$$Q_p = \frac{160\, W \left(\frac{1+e}{W}\right)}{1+\frac{W}{L}}$$

Where, Q_p is the capacity of the roundabout, *W*, e and L are the width, average width of the entrances and the length in the crisscross section in meters respectively. For the roundabout *W = 6.2* m, e = *6.2* m and L = *33.25, 38.56, 32.55* and *47.21* m for inputs 1 to 4 correspondingly.

Table I presents the measured demand on the roundabout at peak time, along with Wardrop's capacity and the overflow in each of the roundabout branches. This table allows us to observe that the roundabout has an average overflow in its capacity of 22.18%. This situation has a direct impact on the increase in the length of the lines of vehicles at the entrances and a significant decrease in the speed of movement and an increase in travel times.

Table I. Demand, capacity and overflow of the gloriet.

Entrance	Movement No.	Number of Vehicles (veh./hour)	Equivalent Vehicles (vehicles / hour)	Entrance (veh./hour)	Between-crossover (veh./hour)	Total Between-crossover (veh./hour)	Qp (veh./hour)	Overflow
1 - Av. Norte	22	34	39	1409	510	1919	1672	15%
	32	101	119					
	33	58	69					
	42	100	156					
	43	176	220					
	44	41	67					
2 - Diag. 38	11	83	126	576	1492	2068	1709	21%
	13	553	966					
	14	434	588					
	15	147	172					
	33	58	69					
	43	176	220					
	44	41	67					
3 - Av. Maldonado	11	83	126	940	1155	2095	1667	26%
	14	434	588					
	15	147	172					
	21	165	257					
	22	34	39					
	24	170	237					
	25	81	103					
	44	41	67					
4 - Av. Oriental	11	83	126	777	1416	2193	1725	27%
	15	147	172					
	21	165	257					
	22	34	39					
	25	81	103					
	31	561	937					
	32	101	119					
	33	58	69					
	35	186	250					

Source: Authors

Simulation of the current state of the roundabout

As a first step, it begins with the simulation of the current situation of the intersection, including all the data acquired in the field. The operation and input of parameters to the software can be consulted in the program's user manual [36]. Once the simulation is built, the model is calibrated with the purpose that it adjusts to the particularities of operation of the case study and in this way, the information extracted from it is valid. The methodology used for the calibration of the model can be consulted in [16]. To determine if the model reaches an acceptable calibration, the results obtained in the field are compared with those obtained by the VISSIM model. The calibration was carried out taking into account the vehicular volumes per entry and exit and speed. Vehicle volumes are compared using the GEH statistic (Geoffrey E. Havers, equation (2)) that is commonly used in traffic analysis [25] and the model is considered calibrated when 85% of the GEH values are less than 5.

$$GEH = \sqrt{\frac{2(M-C)^2}{M+C}} \leq 5$$

Table II shows the comparison GEH of the vehicle volumes taken in the field and thrown by the model for each type of vehicle (shaded values) in each of the roundabout branches, these data show that the GEH values calculated are lower than 5, both individually and globally, therefore, the model is calibrated with a correlation greater than 88% in all cases. Note that the C2S1 and C2S2 tractor-truck, and the C4 4-axle trucks were excluded from the analysis because the volumes measured were not representative.

Table II. Vehicular volumes measured in field (c) and model (m) and, the geh value between both

	Branch	Source or Parameter	Vehicle	Taxi	Cyclist	Motorcycle	Bus TCPU	Bus TCIM	Cam C2-P	Cam C2-G	Cam C3	Cam C4	TC - C2-S1	TC C2-S2	TC C3-S1	TC C3-S2	TC C3-S3	TOTAL VEH
Input Volumes (veh / hour)	1 - Av. Norte	C	454	280	40	176	226	67	73	43	7	0	0	0	0	2	41	1409
		M	443	242	41	170	217	64	69	41	7	0	0	0	0	2	41	1337
		GEH	0.52	2.35	0.16	0.46	0.60	0.37	0.47	0.31	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.94
	2 - Diag. 38	C	257	105	33	54	30	22	11	25	4	3	0	3	0	3	26	576
		M	243	70	34	55	27	22	11	25	3	3	0	3	0	2	27	525
		GEH	0.89	3.74	0.17	0.14	0.56	0.00	0.00	0.00	0.53	0.00	0.00	0.00	0.00	0.63	0.19	2.17
	3 - Av. Maldonado	C	350	194	30	91	223	8	16	21	5	0	0	0	0	0	2	940
		M	347	151	31	83	195	8	14	20	4	0	0	0	0	0	2	855
		GEH	0.16	3.27	0.18	0.86	1.94	0.00	0.52	0.22	0.47	0.00	0.00	0.00	0.00	0.00	0.00	2.84
	4 - Av. Oriental	C	324	138	48	109	23	47	36	17	3	1	0	2	0	3	15	766
		M	302	128	42	100	19	45	34	17	3	1	0	2	0	3	15	711
		GEH	1.24	0.87	0.89	0.88	0.87	0.29	0.34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.02
Output Volumes (veh / hour)	1- Av. Norte	C	456	211	38	107	209	35	37	37	5	3	0	2	0	3	26	1169
		M	427	162	38	95	181	34	32	32	6	4	0	1	0	3	26	1041
		GEH	1.38	3.59	0.00	1.19	2.01	0.17	0.85	0.85	0.43	0.53	0.00	0.82	0.00	0.00	0.00	3.85
	2 - Diag. 38	C	159	77	11	53	32	18	21	17	5	0	0	0	0	2	32	427
		M	124	82	9	49	26	21	26	18	5	0	0	0	0	1	32	393
		GEH	2.94	0.56	0.63	0.56	1.11	0.68	1.03	0.24	0.00	0.00	0.00	0.00	0.00	0.82	0.00	1.68
	3 - Av. Maldonado	C	299	199	30	96	214	17	27	18	4	1	0	0	0	3	4	912
		M	317	170	36	99	209	12	20	21	3	0	0	0	0	3	6	896
		GEH	1.03	2.14	1.04	0.30	0.34	1.31	1.44	0.68	0.53	1.41	0.00	0.00	0.00	0.00	0.89	0.53
	4 - Av. Oriental	C	225	147	49	98	5	65	40	22	2	0	0	3	0	0	22	678
		M	223	120	47	87	6	58	35	19	1	0	0	4	0	0	21	621
		GEH	0.13	2.34	0.29	1.14	0.43	0.89	0.82	0.66	0.82	0.00	0.00	0.53	0.00	0.00	0.22	2.24

Source: Authors

Figure 5 compares the speeds taken in the field and those estimated by the model, the model is considered calibrated by speeds when the correlation between these values is greater than 70%. This figure shows that the model is calibrated as correlations greater than 90% are found both in the circulation ring and in the entrances.

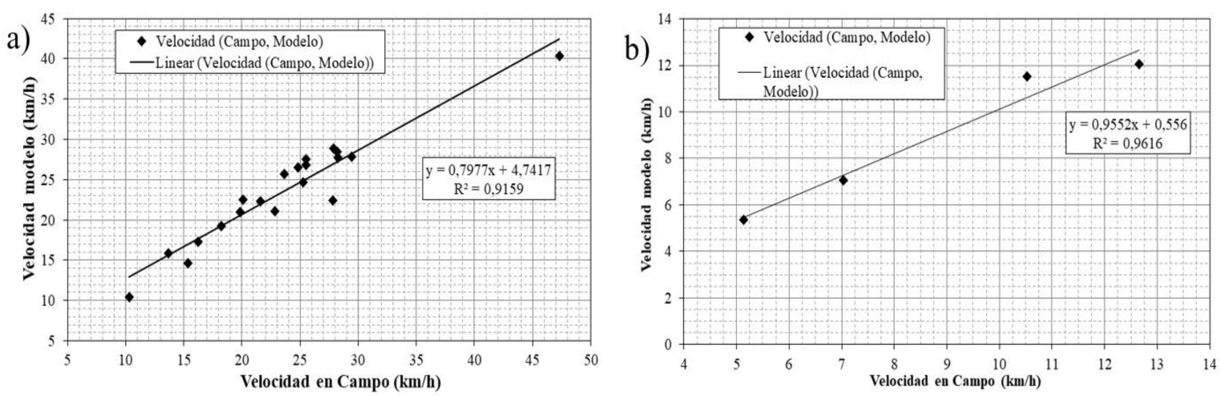

Figure 5. Velocity correlation graph a) in the ring and) in the intersection accesses.

Traffic light solution for the current roundabout

As has actually been established, when the roundabout capacity is reached, a signalized intersection has better performance [4]. This solution allows the route to be made with greater safety by not coming into conflict with the vehicles of the other branches and is technically feasible because the intersection has two lanes at each entrance. The scheduling of traffic control times for the intersection signaling was carried out according to the Webster method, which considers scheduling a 4-phase cycle and allows each of the accesses the exclusive use of the intersection ring. The optimal cycle time was set at 120 seconds (recommended value) with total losses per phase of 7 seconds of all red and yellow times due to saturation flows (Veh / hour. Green) being too low for vehicle volumes present in the accesses and generate an optimum cycle time that is too long.

Modification solution to turbo-roundabout

The Turbo-roundabout is drawn taking as main branches the Av. Norte and Av. Maldonado accesses, making a lag that is reduced to one lane at the entrance of these two lanes to the ring, and only one yields to a lane (see Figure 6). This is because at both entrances and exits the highest percentages of vehicles are registered in the roundabout (see Figure 3).

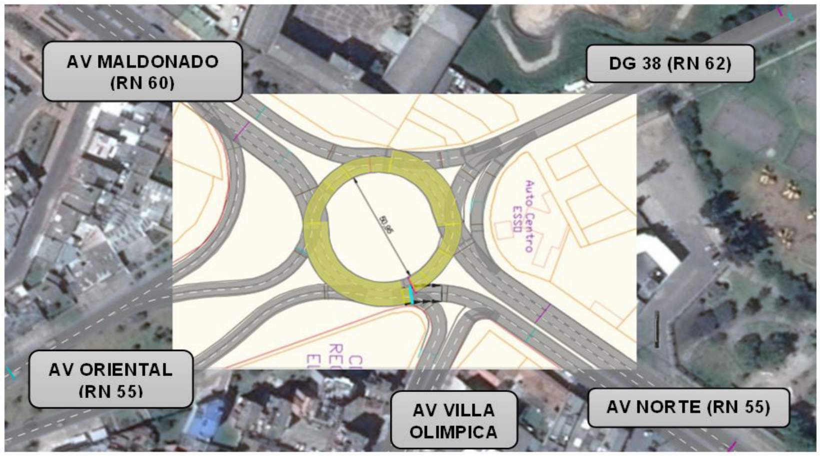

Figure 6. Turbo-roundabout proposed.

Elevated and Depressed Step Solution

Considering the results of Staley's studies [29] and that the analysis of the origin-destination movements of the intersection shows that the movements with the highest demands are between Av Norte and Av Maldonado, an overpass was proposed between them, and for space, requirements move the central ring of the roundabout approximately 10 meters to the north (element 1 in Figure 7).

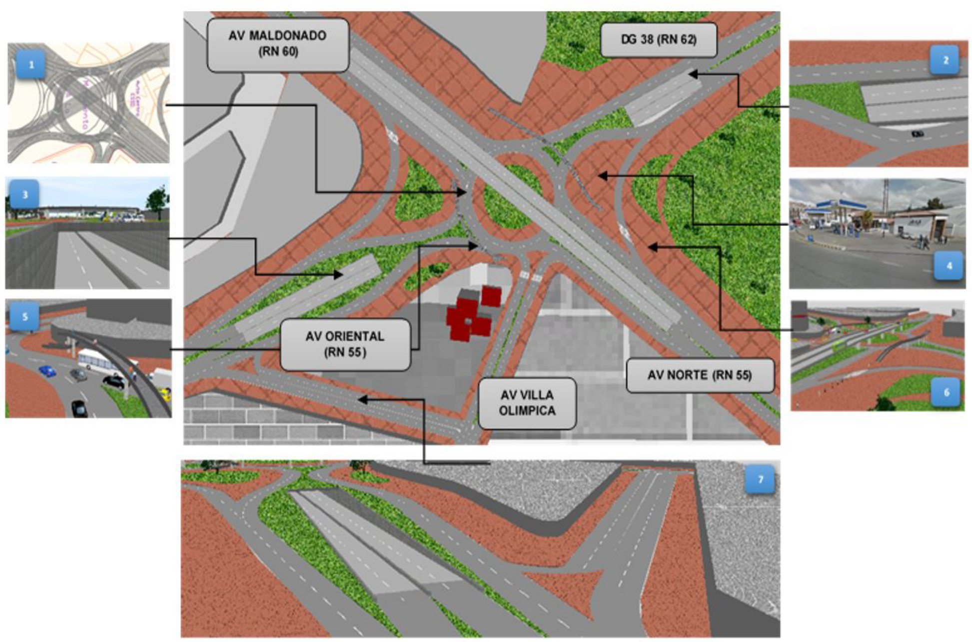

Figure 7. Major changes at the intersection with the implementation of overpass and depressed.

The expansion to the dual carriageway of the Dg road is considered. 38 that is being studied by the municipal and departmental administration (element 2). For the routes between Av Norte and Av Oriental the depressed one was drawn (element 3 in Figure 7) and the removal of the existing service station is considered (element 4 in Figure 7).

Additionally, as element 5, pedestrian bridges are drawn parallel to the overpass for employer mobility in the sector, taking into account the parameters established by the Mayor's Office of Tunja [37], the modification and expansion of the pedestrian areas on the sides of the Av Norte and Av Maldonado (element 6 in Figure 7) and finally, the direct connection between Av Oriental and Av Villa Olímpica in both directions, through a dual carriageway widening the existing road, for the diversion of part of the coming traffic of the Av Oriental (element 7).

Simulations and comparison of the proposed solutions

Figure 8 shows a moment of the simulation of the roundabout in its current form and each of the proposed alternatives. In these, you can see schematically the flow pattern in each considered scenario and the proposed infrastructure. On the other hand, Figure 9 allows us to appreciate the evolution of the volumes for branch number 3 or Av. Maldonado, which presents one of the largest overflows (see Table 1) and that the simulations showed to be the most critical case (is that is, the high difference between the estimated volume and the capacity over time), in this way a numerical estimate of the solutions presented against the current geometry of the roundabout is shown.

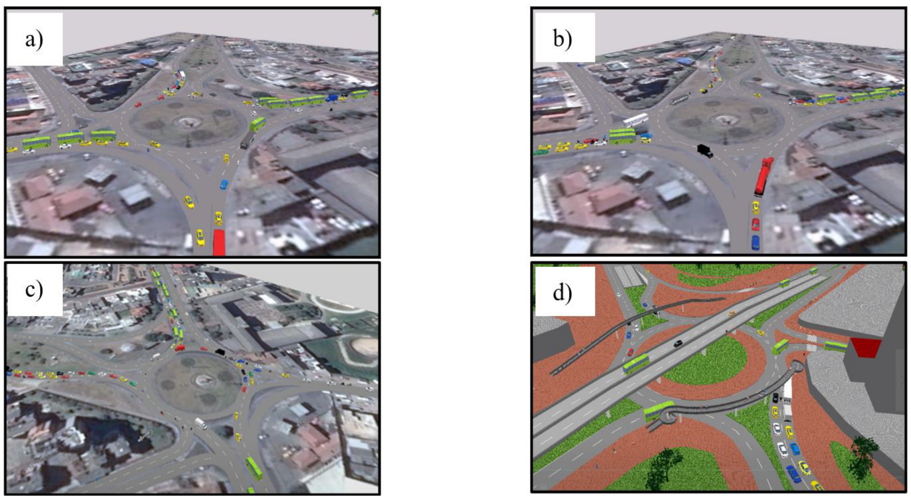

Figure 8. Simulation using the VISSIM model of a) current situation, b) intersection traffic lights, c) turbo-roundabout, and d) Elevated and depressed passage.

Figure 9 shows that the only definitive solution for the roundabout seen from the volume of traffic is the construction of an Elevated and Depressed Passage (Figure 8-d), which allows the volume of traffic projected to be within the capacity of the intersection.

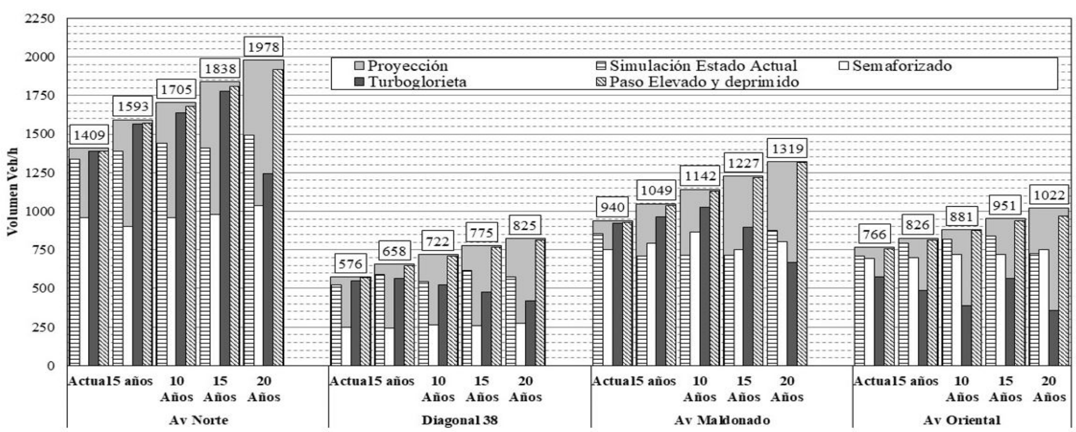

Figure 9. Simulation results in terms of volume for the roundabout.

The traffic lights leads to an immediate decrease in volumes with respect to current values, and they remain constant over time, which prevents the projected volumes of the roundabout from being achieved and therefore an increase in the lines of the roundabouts is expected. The turbo-roundabout is a temporary solution that in an intermediate-term can help alleviate with an investment much lower than the definitive solution and that could be adopted by the municipal administration while they have the resources to build the definitive solution. In this scenario, after the 15-year projection, volumes begin to decrease at the main entrances.

As expected, Figure 10 shows a progressive decrease in entry speeds to a substantial value of 45% in 20 years if the current condition of the roundabout is maintained (see Figure 10-a).

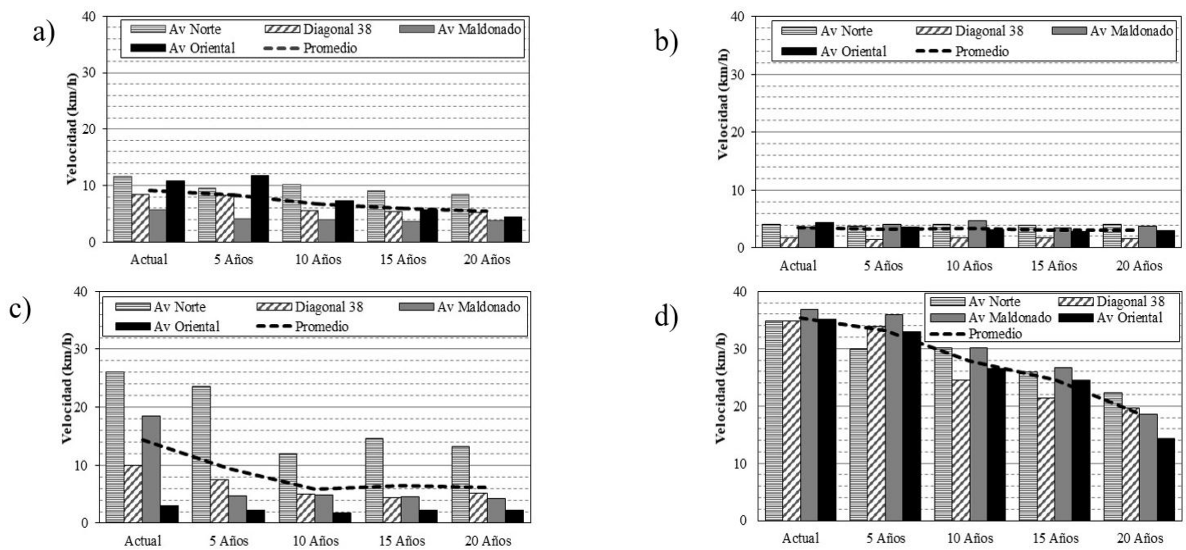

Figure 10. Simulation results in terms of the speed of the entrance to the roundabout for the a) current situation, b) traffic lights c) turbo-roundabout, and d) elevated and depressed passage

In the case of traffic lights (see Figure 10-b), the average speed will be affected by approximately 62% (decrease from 9.16 km / h to 3.5 km / h), which increases delays and stop times trip by intersection and, this situation remains constant in the different periods. On the other hand, in terms of speed, although the turbo-roundabout increases the speed on Av Norte by 47%, it decreases drastically over time to those in current service. The most viable solution from the average speed is the construction of an elevated and depressed crossing (Figure 10-d), which allows an increase of the inside of the roundabout of 386% due to the resignation of traffic that passes over it, and although it is reduced in time, it remains with acceptable speeds in it (average of 18.7 km / h in 20 years).

Conclusions

The micro simulation carried out in the VISSIM software proved to be an adequate tool to reproduce the current situation of the roundabout, obtaining a calibrated model with GEH values lower than 5 for vehicle volumes and correlations higher than 90% both in the average speed in the trafficking ring circulation as the average speed at the entrances, providing evidence for the use of stochastic tracking models, dynamic speeds, and psycho-physical tracking in the case of roundabouts in urban areas.

Starting from detailed characterization of the traffic in the study area and the dynamics around the roundabout of the city of Tunja, it is verified that, for traffic conditions, user behavior (driver), and other particular factors, the roundabout is located operating above capacity.

To improve the mobility of the roundabout, several improvement alternatives that involve changes in the geometry, installation of other branches and / or branches for turbo-roundabouts, and traffic light control were proposed. The results indicate that the installation of traffic lights does not constitute the defined solution to the problem studied, as has been reported in other recent studies in Colombia (eg [5]) because this improvement does not contribute significantly to the increase in the capacity of the intersection [9]. On the other hand, although the installation of a turbo-roundabout increases the speed in one of the branches (Av Norte) by 47%, it does not constitute a solution to the mobility problem in general.

Finally, the definitive solution to increase the speed of circulation and reduce the travel times of roundabouts that have reached their capacity, as is the case studied, require a substantial change in the urban design of the area, where it is necessary to create overpasses between points. high traffic (depressed, elevated, or both), pedestrian areas, expand and / or adapt existing ones and, connect these areas with neighboring parks to create a wide area for pedestrian circulation by the parameters established for adequate urban planning of the cities.

For future research, it is recommended to include a multi-objective analysis that allows evaluating the studied alternatives considering in an integrated way, traffic, polluting emissions, and road conflicts between walkers, bicycles, and motorized vehicles in this type of intersection [38].

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