Evaluation of the Operational Behavior of a Cloverleaf Applying Smart Traffic Lights with the Ramp Metering Methodology

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Summary*– Cloverleafs are infrastructures designed to improve vehicular traffic and safety at intersections. However, problems in its operational behavior can be identified, especially in the loops that converge with the main roads. This is due to the disorderly entry of vehicles, the formation of queues, and the increased probability of collisions. Taking these problems into account, the present investigation proposes a smart traffic lights system with the ramp metering methodology based on the ALINEA algorithm, to evaluate the performance of cloverleaf-like road intersections. The evaluation was carried out in an uneven exchange partial cloverleaf-type of three loops and four direct branches, located in the city of Lima. The evaluation results showed a maximum improvement of 15.8% in average speed, as well as a reduction in average travel time per vehicle of up to 19.1% and an increase in vehicle flow of 30 Veh / h. From these results it is shown that the improvement of these parameters causes a synergy that optimizes the total operation of the cloverleaf.

***Keywords* — Smart traffic lights, ramp metering, ALINEA, cloverleaf.**

I. INTRODUCTION

Vehicle congestion on a city's road networks is a common phenomenon especially during peak hours. According to [1], in its latest Lima traffic report, it ranked the city in the seventh place with the highest vehicle congestion in the world, and with respect to Latin America it ranks second.

A vial cloverleaf-type uneven exchange has the following objectives: to order the vehicle volume; reduce existing bottlenecks; minimize vehicle congestion at specific points; and generate benefits for users, such as the reduction in the use of fuel and oil, and the decrease in the frequency of accidents [2].

However, due to the increase in vehicle demand over time, cloverleaf loses its capacity, causing congestion problems again. In general, these problems appear as points of conflict in the loops that converge towards the main roads, where the disorderly entry of the vehicles generated by the reckless maneuvers of the drivers is generated. Another problem is the inadequate dosage of the tail lengths, which reduces the speed of operation of the vehicles on the main road.

For the case study, a cloverleaf located between two roads with a significant vehicle volume in the city of Lima was selected. The Panamericana Sur that houses about 70,000 vehicles/day and Javier Prado Avenue where around 115,000 vehicles/day circulate [3].

Faced with this problem, different tools can be used to propose alternative solutions, such as simulation models and the Intelligent Transport System (ITS). This research seeks to evaluate the operational behavior of a cloverleaf and optimize its operation by applying smart traffic lights with the ramp metering methodology using the ALINEA algorithm. For this, occupancy detectors were located on the main roads, presence detectors and pass detectors in the loops in order to regulate the time of the traffic lights cycles in real time. The pathways were modeled using the VISSIM microscopic simulation program integrated with the VisVAP module. In this way it was possible to improve the functional characteristics of the cloverleaf such as speed, travel times and vehicular flow.

II. STATE OF THE ART

The search in the literature reveals the efficacy of using a smart control strategy to improve the road confluences of uneven intersections, expressways and urban highways [4] examined dynamic traffic control strategies Dynamic ramp metering and Dynamic speed limit in the field using microscopic simulation. The focus of the study was to compare the efficiency of dynamic traffic control strategies with the uncontrolled case considering indicators such as total travel time, average delay per vehicle and the average number of stops per vehicle. It was observed, in several ramp metering implementations, the reduction of average delays per vehicle of up to 30% and that speed control strategies reduced average delays per vehicle by 7%. The results also revealed that the dynamic traffic control strategies implemented alleviated congestion by increasing the capacity of the section at bottlenecks.

In another investigation [5] evaluated using the local measurement strategy ramp metering ALINEA, a segment of the D-100 highway in Istanbul using Vissim software to perform the micro-simulation. In this study, a 90-second update time of the traffic light cycle was assigned considering different values of the percentage of desired occupancy such as 18%, 25% and 30%. The best results were obtained when using the 25% occupancy percentage which improved the average speed and volume by 16% and 5%, respectively. Additionally, [6] developed a dynamic signal control algorithm applied to an integrated ramp measurement control strategy to improve the operation of highway I-35, in Kansas

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City. Which turns the main road signal red when the traffic queue reaches the vehicular intersection. The results showed a maximum improvement of 15.7% in the average speed and a reduction of the average delay and CO2 emissions in 20.9% and 13.7%, respectively.

Another important study was carried out at the macroscopic level by [7] using large-scale data in the city of Hagzhou, China. Here an adaptive ramp metering control for highways was designed, obtaining that the parameters are updated according to the evolution, in real time, of the vehicle congestion. With this method, they improved the performance of the ramp metering methodology to regulate access traffic and keep the highway traffic flow at a high level of service. The results improved in 8.4% and 4.62% the average speed and 7.2% and 9.48% the average flow. Finally, in the article published by [8] they applied ramp metering to a two-level connection ramp analyzing the geometric parameters, the intensity parameters and the system delays. The existing vehicle load was reduced by 10% and the average delay in road transport was reduced by 48%.

III. ALINEA ALGORITHM

ALINEA adjusts the vehicular dosage of the accesses to maintain the desired occupancy percentage downstream (figure 1). For this purpose, a traffic light guided by an algorithm with a traffic lights cycle is used, which it feedbacks according to the percentage of occupancy is obtained by the sensors of the main roads. According to the formula shown below [9].

$$r(k) = r(k-1) + KR[\hat{o} - Oout(k-1)] \quad (1)$$

Where:

- k = 1, 2, . . . discrete time index.
- r (k): allowable flow capacity in cycle k.
  - rmin: minimum flow capacity
  - rmax: maximum flow capacity
- Oout (k - 1): last vehicle occupation measured downstream (%).
- KR: Regulatory factor to adjust the constant disturbances of the feedback control.
- ô: desired downstream occupancy rate [9].

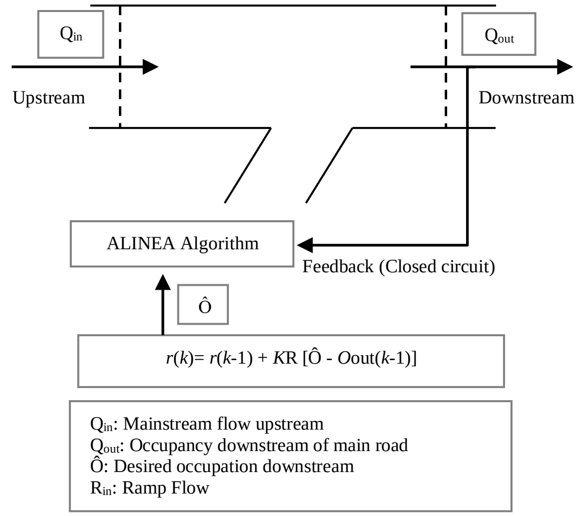

Fig. 1 ALINEA Strategy.

ALINEA has four parameters that must be calibrated: KR, Ô, the location of the downstream detector and the update cycle of each ramp metering r (k) [10] recommend that the KR value be equal to 70 veh / h /% as a standard measure in most ALINEA field or simulation applications. Similarly, the measurement rate r (k) resulting from the ALINEA equation must be within the parameters (rmin, rmax) to avoid closing the ramp. Where rmax must be the maximum allowable flow capacity with an approximate value of 1800 Veh / h and rmin> 0 is the minimum allowable flow value, typically 200 to 400 vph. Furthermore, [11] and [12] suggest that the location of the downstream detector should be at the point caused by congestion, generally located between 40 and 500 m downstream from the end of the ramp. Local ramp metering strategies are activated at each time interval T, whose value is typically selected in the range of 20 to 60 s; however, if the update time is minimal, the location of the detector should be close to the entrance ramp, otherwise congestion may occur between the confluence and the detector [10]. Similarly, [11] recommends that the desired occupancy rate has a value of 0.30.

IV. CASE STUDY AREA

The uneven road exchange is comprised between two main avenues, this infrastructure is of partial cloverleaf-type with three loops and four collecting lanes. For the investigation, the loops were evaluated simultaneously due to the observed vehicle congestion, and the lengths of queues generated in the cloverleaf admissions. Said loops are uneven and have single-lane routes, which converge towards the main routes. The avenues that make it up are the Javier Prado which has 4 lanes in each direction, and the Panamericana Sur, which is made up of three lanes for both directions. As shown in figure 2.

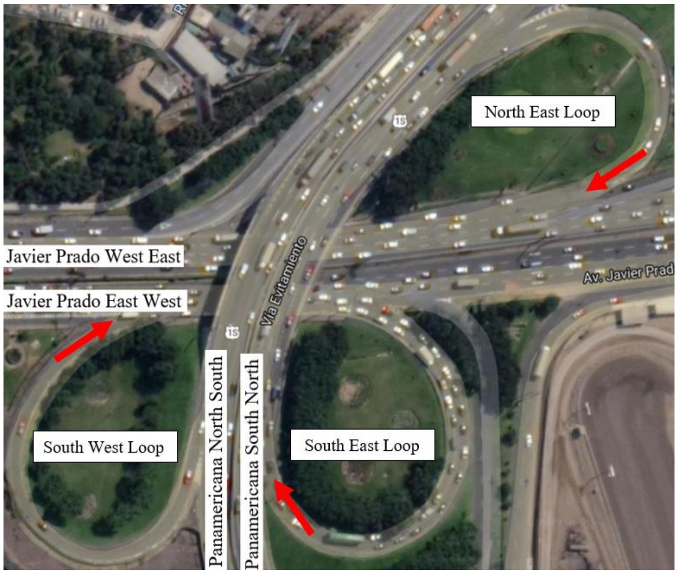

Fig. 2 Case study area.

The vehicle capacity was carried out considering the TomTom website database which collects traffic information in real time. Figure 3 shows a greater vehicular flow at night. It is for this reason that the night peak hour was chosen for the vehicle count.

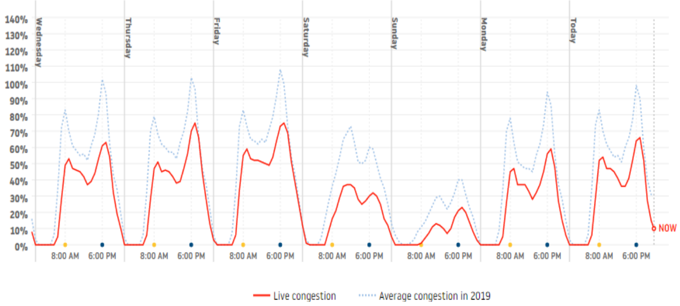

Fig. 3 Lima Vehicle Congestion, by TomTom (2019).

V. Methodology

To quantify the improvement in vehicular operation in cloverleaf, a traffic micro-simulation is performed. There are many simulation tools to study and analyze confluence problems, for example Quadstone Paramics, S-Paramics, AIMSUN, PTV Vissim and many others. For the case study, we use PTV Vissim 9, with its VisVAP module.

PTV VISSIM is a microscopic simulation program based on the driving behavior model of Wiedemann 74, proposed by [13] and [14]. PTV VISSIM is developed by PTV AG (Planung Transport Verkehr Aktiengesellschaft) and written in C ++ in object-oriented programming [15].

The design, calibration and validation were carried out, to then implement the proposal by applying ramp metering in each loop of the cloverleaf. The Wiedemann 74 models were used to perform the calibration and validation of the simulation. Which are based on the psychophysical behavior of the driver and are defined as free driving, approach, tracking and braking. The calibration was carried out by comparing the speeds and travel times obtained in critical segments, both in the field and in the model, to do this, the parameters were iterated in the Wiedemann 74 model until a confidence level of 95% was achieved, with a nonparametric statistical test of mean difference. Model validation was performed with new field data and following the same procedure, but without modifying Widemeann 74 parameters, obtaining a 95% confidence level.

The traffic lights were implemented in each loop of the cloverleaf applying the ramp metering methodology. For this, the ALINEA local feedback control algorithm, proposed by [11] was used. This strategy aims to keep the occupation percentages of the main roads at a predetermined value. For this purpose, the KR values, the desired occupancy percentages and the distances of the occupancy detectors are varied. The logic of this methodology is shown in figure 4.

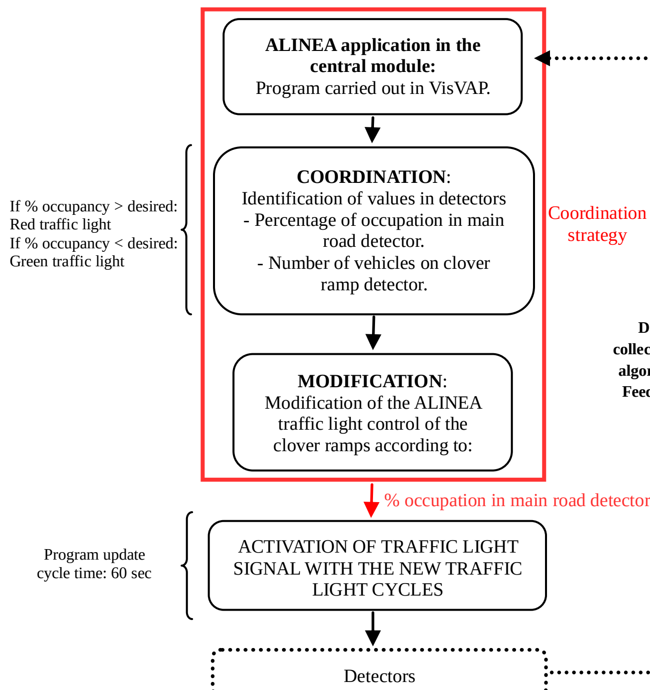

Fig. 4 ALINEA strategy diagram applied to cloverleaf.

VI. Model Simulation

Firstly, for the Vissim simulation, the data was collected. These were carried out in two working days with a MAVIC PRO drone. The first filming was aimed at calibrating the model, for this the chosen time was Tuesday, February 18, 2020 from 6:00 p.m. at 8:00 p.m. The second filming was made for the validation of the model and was chosen on Tuesday, February 25, 2020 from 6:00 p.m. at 8:00 p.m. With these films, the vehicle capacity, travel times in critical segments, stop times of the transport lines and other variables required for the simulation were obtained. Figure 5 shows the flowchart of the cloverleaf evaluated.

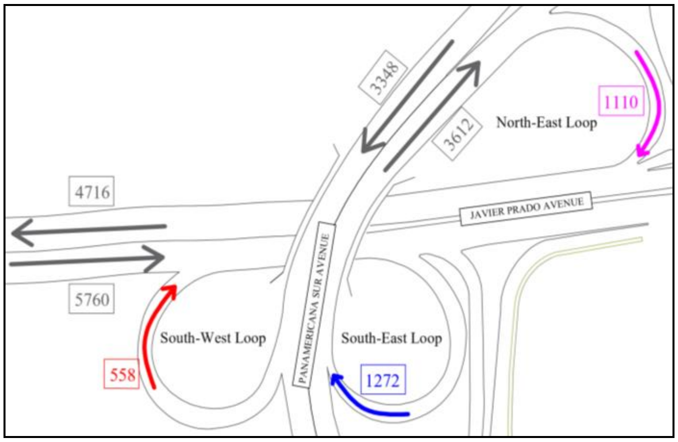

Fig. 5 Cloverleaf flowchart (Veh/h)

Secondly, the modeling of roads with their respective connectors was carried out according to the measurements taken in the field. The desired speeds were then entered on the main roads. Likewise, speed reduction areas were in the cloverleaf loops, this in order to represent the speed of operation of the vehicles. Subsequently, the vehicle capacity and the relative flows of the ramifications were entered. Then the whereabouts of the transport lines were placed, with their respective time stop's distribution. Finally, priority rules and conflict areas were assigned to simulate the peculiarities of the behavior of drivers in cloverleaf.

Third, to perform the calibration, the Wiedemann 74 driving behavior parameters were varied. The objective of the calibration was to minimize the differences between the behavior observed in the field and the simulation results. This was done with the values obtained from the travel times in the critical segments of a random sample of vehicles. It was determined that the number of seeds that fit the case was 40, with an increase of 1, in 25 runs. The values obtained both in the model and in the situation were compared with a nonparametric statistical test of mean difference, with 95% confidence. Once the calibration of the model was achieved, the validation proceeded, for this the field data were taken again, these were entered into the model, and the same procedure was performed, obtaining a value within the non-rejection zone, with 95% reliability.

Finally, once the design was established, the dynamic traffic lights were programmed in the VisVAP module, verifying their correct operation. Subsequently, the traffic light system was placed in each loop with the parameters adapted to each case. Three types of detectors were located per loop: proximity, percentage of occupation and demand, according to the requirements of the roads, since each one is a slightly different situation both in the demand for the loops and in the demand for the main road. Figure 6 shows the detectors used in a loop.

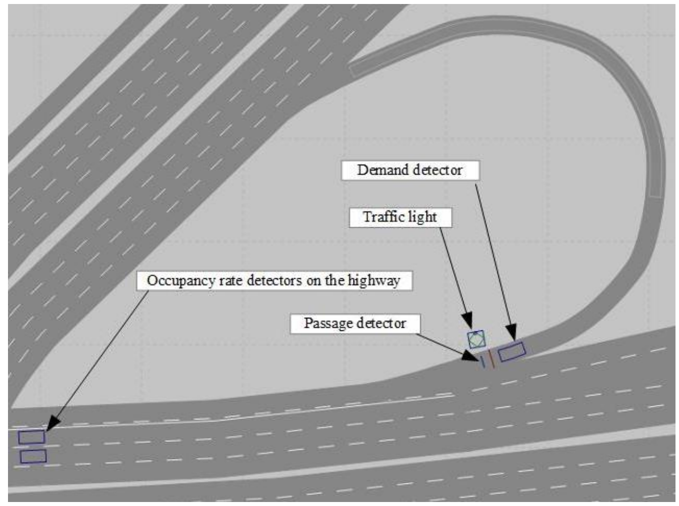

Fig. 6 Detectors in the North – East loop

VII. Results

The parameters of the controllers were different for each case. These were simulated several times to calibrate them, until obtaining optimal results. In the loops where greater instability in driving behavior was observed, a higher value was assigned for the KR factor.

For the desired occupancy percentages, the value of 0.3 was used for the three loops, which is recommended by [11] authors. As mentioned in the ALINEA algorithm explanation, the distances of the occupancy detectors can vary from 40 to 500 m. downstream. Taking the driving behavior into the cloverleaf into account, the detector distances were assigned. The update cycle that best suited the cloverleaf evaluated was 60 seconds. Table 1 shows the results obtained.

TABLE 1
PARAMETERS OF THE TRAFFIC LIGHTS CONTROLLERS.

	Cloverleaf loops		
Parameters:	South – East Loop	North - East Loop	South – West Loop
KR (regulator factor)	80	70	80
Ô (desired occupancy percentage)	0.3	0.3	0.3
Occupancy detector distance	40	70	220
Update cycle	60	60	60

Figure 7 shows the location of detectors and traffic lights.

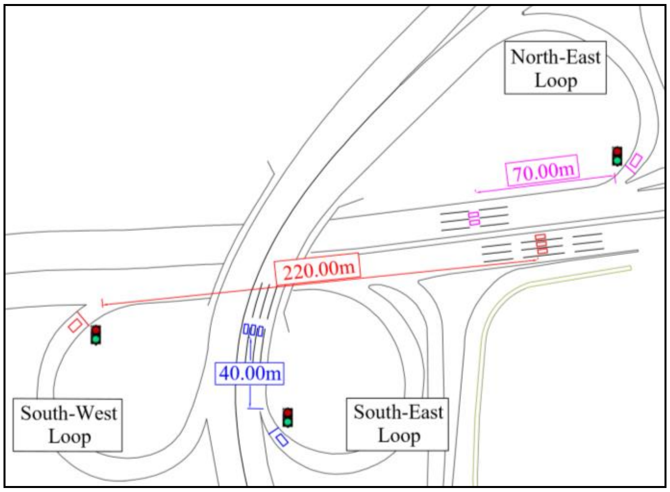

Fig. 7 Distribution of detectors and traffic lights in cloverleaf.

Three parameters were evaluated to measure vehicle operation in cloverleaf: average travel times, average speed, and vehicle flow.

First, the average travel times were estimated by measuring the time it took for vehicles to get from one point to another during the simulation runs. In the simulated cloverleaf, 3 critical segments were taken for the analysis, which were located downstream of the confluences. Table 2 shows the results of the travel times in each loop. Here it is verified that the travel times are longer without traffic light control. These results show that dynamic control is required in each loop, so that vehicles can circulate greater fluidity.

TABLE 2
TRAVEL TIMES IN THE CONFLUENCE OF LOOPS

		Timeslots (s)				
	Loops	600-1200	1200-1800	1800-2400	2400-3000	3000-3600
without traffic light control	South-West	7.5	7.8	8.6	9.1	10.3
	North-East	8.0	8.0	8.0	8.0	8.0
	South-East	14.3	16.5	16.2	16.0	16.3
with traffic light control	South-West	7.5	7.5	7.5	7.5	7.6
	North-East	8.0	8.0	7.9	8.0	8.0
	South-East	13.3	13.3	13.5	13.3	13.3

Table 3 shows the percentage decrease in each loop. A maximum reduction in travel time of 19.1% is observed, which was in the south-east loop.

TABLE3
PERCENTAGE OF IMPROVEMENT IN TRAVEL TIMES

	Travel times (s)		%
Loops	Without control	With control	
South-West	8.7	7.5	15.2
North-East	8.0	8.0	0.7
South-East	15.9	13.3	19.1

Second, the speeds in the critical segments were evaluated. The following graphs show the differences in velocities over time. These show that when you have a dynamic traffic light control you can improve the speeds of the vehicles inside the cloverleaf.

Fig. 8 Comparison of speeds in the south-west loop.

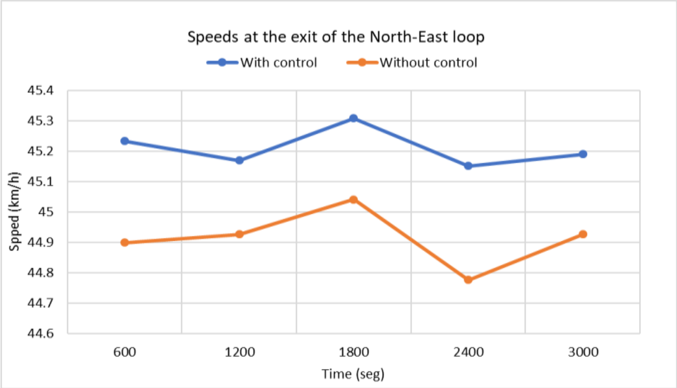

Fig. 9 Comparison of speeds in the north - east loop.

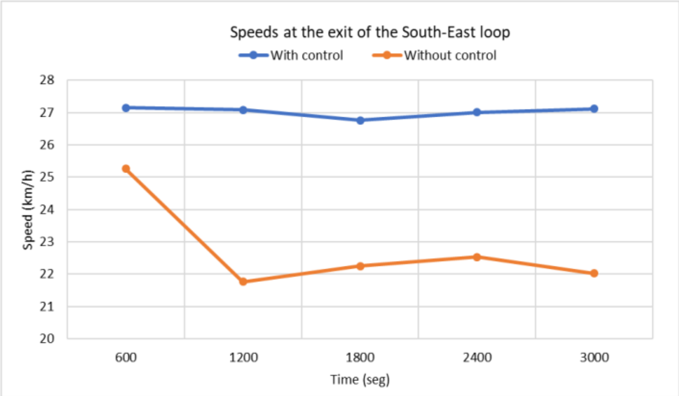

Fig. 10 Comparison of speeds in the south – east loop

Table 4 is shown below, in which the percentage increase in speeds is observed when dynamic traffic light control is applied. The maximum value was obtained in the south-east loop of 15.8%.

TABLE 4
PERCENTAGES OF IMPROVEMENT IN THE AVERAGE SPEEDS

	average speeds (km/h)		%
Loops	With control	Without control	
South-West	42.1	47.9	12.1
North-Easy	44.9	45.2	0.7
South-East	22.8	27.0	15.8

Finally, the vehicle flow was evaluated. This increased by 0.3% with the traffic light control, which shows that an adequate vehicle dosage in cloverleaf loops helps to improve overall flow. Although the percentage is not a very high figure, it represents a total of 30 additional vehicles that were able to transit the cloverleaf in a period of 1 hour.

VIII. CONCLUSIONS

With the use of ramp metering in the cloverleaf, the separation of vehicles on the main road is better used, so that vehicles do not have to slow down or stop. This produces an increase in the average speed of operation in all loops of the cloverleaf. The maximum value was obtained in the south-east loop, achieving an increase of 15.8% in the average speed of operation.

The longest travel times occur when there are bottlenecks at the entrances to cloverleaf. This increases the aggressiveness of drivers when entering the main road increasing the chances of collision between vehicles. With the application of ramp metering, it was possible to reduce the average travel time in the three loops of the cloverleaf, achieving a maximum decrease in the south-east loop of 19.1% in the average travel time.

Implementing smart cloverleaf traffic lights improves fluency and reduces conflict at junctions. This causes a synergy that optimizes the total operation of the cloverleaf. This can be confirmed by increasing average speeds and decreasing travel times.

The number of vehicles that transit the cloverleaf increased by 30 units when the traffic light control was active, which represents a 0.3% increase in capacity. This evidences the adequate dosage of the cloverleaf's capacity with the improvement proposal.

Smart transportation systems help cloverleaf-type exchanges reduce or eliminate congestion problems. Cloverleaf ramp metering is a proposal that has the advantage of optimizing the capacity of existing infrastructure. The ALINEA algorithm in cloverleaf loops, from the entry of a vehicle on the highway, allows calculating the optimal dosage for the following vehicles. Therefore, it ensures that the trip is carried out with greater fluidity, speed and comfort.

IX. REFERENCES

[1] TomTom (2019) Lima Traffic Report. [Online]. Available: https://www.tomtom.com/en_gb/traffic-index/lima-traffic

[2] *A policy on Geometric Design of Highways and Streets,* American Association of State Highway and Transportation Officials (ASHTO), 2018.

[3] *Encuesta de recolección de información básica del transporte urbano en el área metropolitana de Lima y Callao*, Japan International Cooperation Agency (JICA), 2013.

[4] Kesten and M. Ergün, "Efficiency analysis of the dynamic traffic control for an urban highway," *EURASIP Journal on Wireless Communications and Networking*, vol. 52, December 2015.

[5] Abuamer and H. Celikoglu, "Local Ramp Metering Strategy ALINEA: Microscopic Simulation Based Evaluation Study on Istanbul Freeways," *Transportation Research Procedia.*, vol. 22, pp. 598-606, 2017

[6] Ghiasi, D. Hale, J. Bared, A. Kondyli and J. Ma, "A Dynamic Signal Control Approach for Integrated Ramp and Mainline Metering," *21st International Conference on Intelligent Transportation Systems (ITSC)*, Maui, HI, 2018, pp. 2892-2898.

[7] Chen, W. Lin, Z. Yang, J. Li, and P. Cheng, "Adaptive Ramp Metering Control for Urban Freeway Using Large-Scale Data," *IEEE Transactions on Vehicular Technology*, vol. 68, no. 10, pp. 9507-9518, Oct. 2019.

[8] Novikov, I. Novikov, A. Shevtosa, and A. Burlutskaya, "ПРИМЕНЕНИЕ СИСТЕМЫ RAMP METERING НА ДВУХУРОВНЕВЫХ РАЗВЯЗКАХ," *The Russian Automobile and Highway Industry Journal*, vol. 16, no. 2, pp. 166-180, 2018.

[9] Papageorgiou, H. Hadj-Salem, and F. Middleham, "ALINEA Local Ramp Metering. Summary of Field Results," *Transportation research Record,* vol. 1603, pp. 90-98, 1997.

[10] M. Papageorgiou, E. Kosmatopoulos, I. Papamichail, and Y. Wang, "A Misapplication of the Local Ramp Metering Strategy ALINEA," *IEEE Transactions on Intelligent Transportation Systems*, vol. 9, no. 2, pp. 360-365, June 2008.

[11] Papageorgiou, H. Hadj-Salem, and J. Blosseville, "ALINEA: A local feedback control law for on-ramp metering," *Transportation Research Record,* vol. 1320, pp. 58-64, 1991.

[12] Chu, H.X Liu, W. Recker, and H.M, Zhang, "Performance evaluation of adaptive ramp-metering algorithms using microscopic traffic simulation model," *Journal of Transportation Engineering,* vol. 130, no. 3, pp. 330-338, 2004.

[13] R. Wiedemann, "Modeling of RTI-Elements on Multi lane Roads," in *Advanced Telematics in Road Transport Edited by the Commission of the European Community*, vol. DG XIII, 1991.

[14] Fellendorf and P, Vortish, "Microscopic Traffic Flow Simulator VISSIM," *Fundamentals of Traffic Simulation, International Series in Operations Research & Management Science*, vol. 145, pp. 63-93, 2010.

[15] *VISSIM 5.40 User Manual,* PTV AG, 2011.