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Evaluation of Adaptive Traffic Signal Control to Improve Pedestrian–Vehicle Interaction at Urban Intersections

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Abstract*– Urban intersections located near areas with high pedestrian activity often experience elevated traffic demand and significant delays between pedestrians and vehicles, increasing accident risk and travel times. In this context, this study evaluates the effectiveness of an adaptive traffic signal system in reducing pedestrian–vehicle interaction conflicts, considering both formal crossings at intersections and informal pedestrian crossings or non-conventional desire lines located outside designated crosswalks. Three cases were modeled using VISSIM software: (1) Case 1, representing the intersection under existing conditions, with its current geometry and conventional signal control; (2) Case 2, similar to the first, incorporating a geometric redesign and a reorganization of pedestrian and vehicular flows, including bus stop relocation and pedestrian channelization; and (3) Case 3, which maintains the geometric adjustments from Case 2 and introduces an adaptive signal control system with dynamic phase timings based on real-time user demand. The results indicate that Case 1 exhibits the highest levels of delay and conflicts. In Case 2, the geometric redesign reduces conflicts by approximately 40%, but increases vehicular delay by about 25%. Finally, Case 3 achieves a cumulative reduction of nearly 47% in vehicular delay and improves pedestrian flow conditions, demonstrating that adaptive traffic signal control enhances both vehicular mobility and pedestrian safety at formal and informal crossing locations.

***Keywords*-- adaptive traffic signal, microsimulation, pedestrian–vehicle interaction, pedestrian mobility, urban intersection.**

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I. Introduction

In urban contexts where unpredictable traffic behaviors prevail—such as the circulation of informal public transport, aggressive driving patterns, and pedestrian crossings outside designated areas—traditional traffic signal systems exhibit significant limitations. Fixed-time signal control, still widely used in many cities, fails to adapt to the dynamic conditions of vehicular and pedestrian flow, assigning green times that do not always correspond to actual demand or safety requirements. Even conventional actuated systems, which adjust signal phases based on traffic volumes or waiting times, prove insufficient in environments where the primary issue is not the number of users, but the frequency and intensity of conflicts among them. Unlike more regulated contexts where compliance with traffic rules reduces the need for intervention, in environments characterized by disordered behavior, pedestrian–vehicle interaction—particularly at intersections lacking effective control—becomes a critical factor directly affecting both operational efficiency and road safety.

Several studies have implemented adaptive traffic signal control by adjusting phase timings based on vehicular or pedestrian flow, achieving reductions in delays and conflicts [1]. Approaches based on fuzzy logic and deep learning have also been used to adapt signal control in real time [2]. Geometric redesign strategies, including relocation of bus stops, crosswalks, and pedestrian channelization, have demonstrated improvements in safety and circulation [3]. Decentralized systems allow each intersection to optimize its operation autonomously according to local conditions [4], while hierarchical approaches organize vehicles into intelligent platoons, prioritizing critical trajectories [5].

In this context, mesoscopic simulation has played a key role in validating these solutions in complex environments [6]. Hybrid models integrate adaptive control with predictive techniques such as neural networks or wavelets, improving the allocation of crossing times [7]. Some systems classify vehicles by type or turning movement to reduce waiting times [8]. Complementary physical solutions, such as reversible lanes and pedestrian sensors, have also been proposed to mitigate conflicts [9]. The most effective strategies combine intelligent control with physical redesign, particularly in environments with high pedestrian vulnerability [10].

In this study, pedestrian–vehicle interaction is defined as the set of operational interferences that occur when pedestrians and vehicles share the crossing space without adequate temporal or spatial separation. These interactions manifest as informal pedestrian crossings outside designated crosswalks, public transport stops that block traffic lanes, and turning maneuvers by large vehicles that encroach upon pedestrian crossing areas.

This research does not aim to optimize individual user behavior, but rather to reduce the frequency and intensity of these conflictive interactions through a more efficient temporal allocation of crossing opportunities, supported by geometric redesign and the implementation of an adaptive traffic signal control system.

II. METHODOLOGY

A. Study Area Description

The study was conducted at the intersection of Av. Venezuela and Av. Universitaria, a critical node in the city of Lima, Peru, characterized by high volumes of vehicular and pedestrian traffic, as well as frequent conflicts among users.

Fig. 1 shows the location of the study area and its immediate surroundings.

Fig. 1. Location of the study area.

B. Data Collection

Manual traffic counts and drone-based recordings were used to obtain vehicular volumes, pedestrian flows, and circulation patterns. These data were used to calibrate the simulation models.

The vehicular volumes observed during the study period for the south, east, and west approaches are presented in Tables I, II, and III, respectively, and constitute the input data used for modeling and simulation.

TABLE I. VEHICULAR FLOW AT THE SOUTH APPROACH

CONTROL HOURS	SOUTH APPROACH			
	23	**21**	**24**	**22**
10:30:00 - 10:42:00	0	0	0	197
10:42:00 - 10:54:00	2	0	0	130
11:54:00 - 11:06:00	0	1	0	173
11:06:00 - 11:18:00	0	2	0	83
11:18:00 - 11:30:00	0	3	0	111
TOTAL	**2**	**6**	**0**	**694**

TABLE II. VEHICULAR FLOW AT THE EAST APPROACH

CONTROL HOURS	EAST APPROACH			
	32	**34**	**33**	**31**
10:30:00 - 10:42:00	263	0	19	29
10:42:00 - 10:54:00	142	0	2	16
11:54:00 - 11:06:00	185	0	3	33
11:06:00 - 11:18:00	165	0	1	19
11:18:00 - 11:30:00	154	0	3	28
TOTAL	**909**	**0**	**28**	**125**

TABLE III. VEHICULAR FLOW AT THE WEST APPROACH

CONTROL HOURS	WEST APPROACH			
	41	**42**	**44**	**43**
10:30:00 - 10:42:00	0	21	0	74
10:42:00 - 10:54:00	0	13	0	68
11:54:00 - 11:06:00	0	26	0	70
11:06:00 - 11:18:00	0	13	0	73
11:18:00 - 11:30:00	0	14	0	54
TOTAL	**0**	**87**	**0**	**339**

Fig. 2 presents the vehicular flow diagram of the intersection, identifying the main circulation and turning movements observed during fieldwork.

Additionally, Fig. 3 shows the predominant pedestrian flows within the study area, including both formal and informal crossings recorded during the counts.

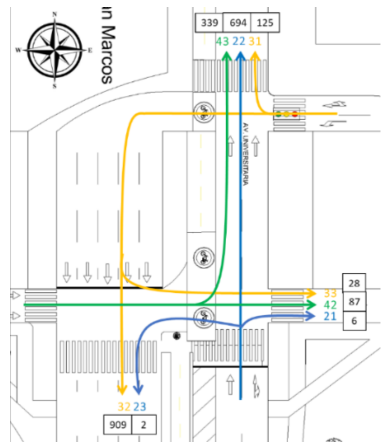

Fig. 2. Vehicular flow diagram of the Av. Venezuela & Av. Universitaria intersection.

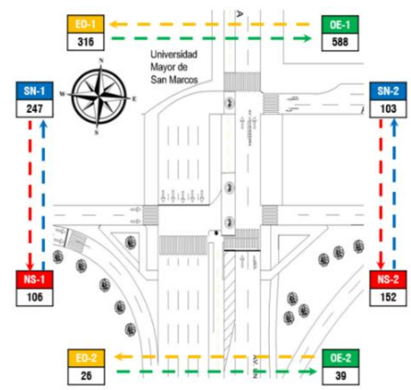

Fig. 3. Pedestrian flow at Av. Venezuela & Av. Universitaria.

C. Modeling and Simulation in VISSIM

Three scenarios were developed using the PTV VISSIM 9 software:

- **Case 1:** Current state of the intersection, including existing geometry and signal control.
- **Case 2:** Current state with a reorganization of traffic circulation and geometric adjustments.
- **Case 3:** Final scenario incorporating adaptive traffic signal control and dynamic allocation of crossing times for both vehicular and pedestrian flows.

D. Configuration of Signal Cycles and Phases

The intersection was modeled using a phase-based signal control scheme. In Cases 1 and 2, a fixed-time control was applied with constant green times throughout the simulation, representing conventional operation without demand responsiveness.

In Case 3, an adaptive control system was implemented to dynamically adjust phase durations based on observed vehicular and pedestrian accumulation, while respecting minimum and maximum safety constraints. The system prioritizes movements with higher levels of delay and redistributes green time to reduce interference between flows.

E. Logic of the Adaptive Traffic Signal Control System

The adaptive traffic signal system implemented in Case 3 was based on a demand-responsive control logic, programmed using the signal control module of PTV VISSIM. This logic considers real-time information on the accumulation of vehicles and pedestrians at the intersection approaches, allowing dynamic adjustment of signal phase durations.

For the vehicular component, the system monitors queue length and stop frequency along the approach lanes. When vehicular accumulation exceeds a predefined threshold, the system extends the green time of the corresponding phase, reducing queue formation and unnecessary stops.

For the pedestrian component, the adaptive control evaluates pedestrian accumulation in waiting areas and pre-crossing waiting times. In the presence of high accumulation or prolonged delays, the system prioritizes the pedestrian phase by allocating longer crossing times, thereby reducing the likelihood of informal or conflictive crossings.

The redistribution of green time is performed within predefined minimum and maximum safety limits for each phase, ensuring that system operation does not generate spillback or additional conflicts between vehicular and pedestrian movements. The adaptive control aims to balance vehicular efficiency with the safety of vulnerable users by dynamically prioritizing movements with higher conflict levels.

F. Definition and Classification of Pedestrian-Vehicle Conflicts

In this study, a pedestrian–vehicle conflict is defined as any interaction in which the trajectory, speed, or maneuver of one user is altered due to the simultaneous presence of the other within the crossing area, generating operational interference or potential safety risk.

Conflicts were identified through the analysis of the VISSIM microsimulation, considering forced stops, sudden speed reductions, and trajectory overlap between pedestrians and vehicles.
To evaluate the impact of the analyzed interventions, conflicts were classified into the following types:

a) Informal pedestrian crossing: Pedestrians crossing outside designated crosswalks following non-conventional desire lines, causing vehicular stops and evasive maneuvers.

b) Public transport stopping: Vehicles stopping near the intersection, partially or fully blocking lanes and affecting flow continuity.

c) Heavy vehicle turning maneuvers: Large vehicles requiring additional space and time to complete turns, occupying multiple lanes or encroaching on pedestrian crossing areas.

d) Signal phase overlap: Simultaneous movement authorizations without adequate temporal or spatial separation, increasing the likelihood of interference.

G. Comparison of Control Schemes

The main difference among the three evaluated cases lies in the allocation of green time. While Cases 1 and 2 operate under fixed-time control without responsiveness to demand variations, Case 3 introduces an adaptive scheme that redistributes crossing time according to observed operating conditions.

This distinction allows isolating the effect of geometric redesign from that of signal control, facilitating the evaluation of each intervention's contribution to reducing delays and conflicts.

H. Model Assumptions and Scope

The analysis is based on a microsimulation model representing typical peak-hour conditions, using field-observed vehicular and pedestrian volumes. Average user behavior is assumed, without considering incidents, signal failures, or adverse weather conditions.

Calibration was performed by comparing observed and simulated data, ensuring a consistent representation of pedestrian–vehicle interaction. The results allow evaluation of the relative impact of the proposed interventions at the studied intersection, without extrapolating absolute values to other urban contexts.

I. Simulation Model Validation

Model validation was performed using a Randomization Test comparing field-observed indicators with those obtained from the VISSIM simulations. The null hypothesis assumes no significant differences between both datasets.

The statistic (x_1 - x_2) was found to be close to zero and within the 95% confidence interval, leading to the non-rejection of the null hypothesis. This confirms that the calibrated model adequately represents real intersection conditions.

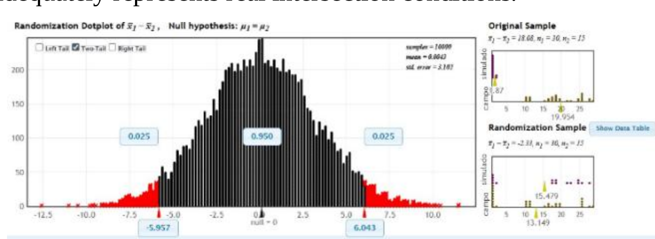

Fig. 4. Model calibration using Randomization Test.

J. Methodological Diagram

Fig. 5 presents the methodological workflow used in this study. The methodology is structured based on the simulation of different operational scenarios at the analyzed intersection, in order to evaluate the impact of geometric and technological improvements on traffic efficiency.

Based on the definition of scenarios and the collection of demand data and operating conditions, the simulation process includes the current state (E1), a version with geometric redesign (E2), and a third alternative that incorporates adaptive traffic signal control in combination with geometric redesign (E3).

Subsequently, performance indicators such as delay, queue length, conflicts, and travel time are evaluated. Based on these results, conflict reduction across scenarios is analyzed, and the impact of each component is assessed separately, identifying those with the greatest influence on improving traffic efficiency.

This approach enables a cross-analysis of the relative contribution of each configuration, facilitating evidence-based decision-making.

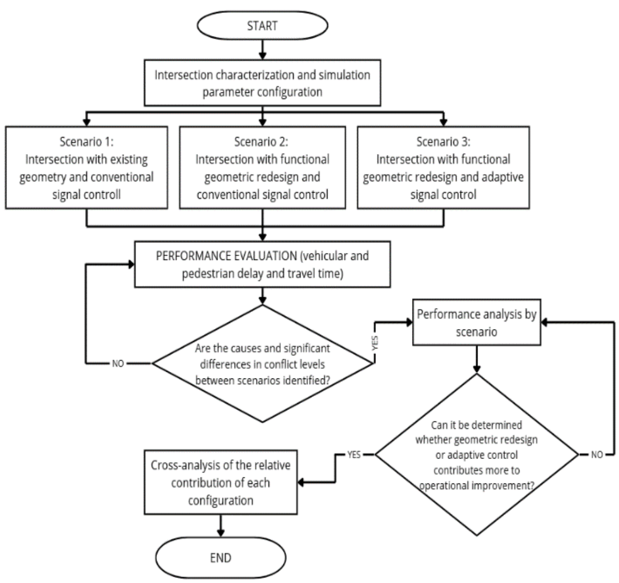

Fig. 5. General methodological framework used in the study.

K. Tools Used

The following tools were used for the development of this study:

- PTV VISSIM 9: Traffic microsimulation software used to model vehicular and pedestrian behavior at the study intersection, allowing the evaluation of different signal control scenarios.
- Mobility Data Acquisition System (ERM): Unmanned aerial device (drone) used to collect real vehicular and pedestrian flow data. This system provided accurate information during peak hours, which was used for calibration of the base model.

III. TECHNICAL INTERVENTION

This section describes the geometric and operational modifications implemented in Cases 2 and 3. These interventions aim to reorganize pedestrian and vehicular flows and to incorporate an adaptive traffic signal control scheme. Case 1 represents the baseline condition and does not involve any intervention; therefore, its description is presented in the Methodology section.

The base configuration of the intersection corresponding to Case 1 is shown in Fig. 6.

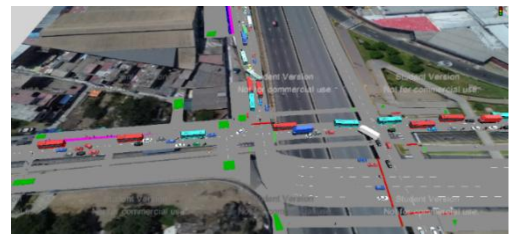

Fig. 6. Base configuration of the intersection – Case 1.

A. Case 2: Intersection with Functional Geometric Redesign and Conventional Signal Control

Case 2 incorporates a functional geometric redesign aimed at organizing pedestrian and vehicular flows. Pedestrian crossings were relocated to areas with higher visibility, and physical channelization elements, such as barriers, were implemented to reduce crossings outside designated areas.

Additionally, the lane configuration was modified by separating turning movements from through traffic to reduce trajectory overlap. Public transport stops were relocated away from the immediate intersection area to prevent blockages and improve traffic flow continuity.

Fig. 7 shows the resulting geometric configuration of Case 2.

Fig. 7. Functional geometric redesign of the intersection – Case 2.

B. Case 3: Intersection with Functional Geometric Redesign and Adaptive Signal Control

Case 3 retains the geometric modifications implemented in Case 2 and incorporates an adaptive traffic signal control system programmed within the signal control module of PTV VISSIM. This system dynamically adjusts phase durations based on the observed vehicular and pedestrian demand during the simulation.

The control prioritizes pedestrian crossing when high accumulation levels or prolonged waiting times are detected, and redistributes green time toward vehicular movements experiencing higher queue lengths or frequent stops. The allocation of signal timings respects minimum and maximum safety constraints to prevent blockages at critical approaches.

Fig. 8 presents the configuration corresponding to Case 3.

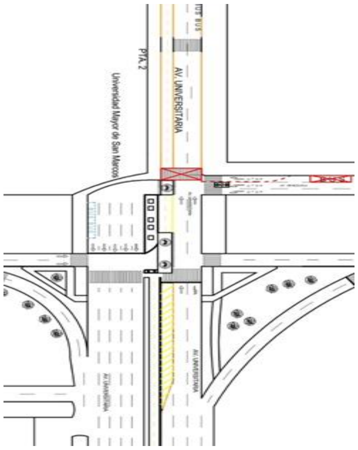

Fig. 8. Intersection with geometric redesign and adaptive signal control – Case 3.

IV. RESULTS

The results obtained from the simulation of the three scenarios in PTV VISSIM allowed for a comparative performance analysis of the intersection, considering the main defined indicators: average delay per vehicle, average travel time, vehicle speed, pedestrian waiting time, and number of conflicts per hour.

To evaluate the variation of these indicators with respect to Case 1, the following equation (1) was used:

$$V = ((Case_i - Case_1)/Case_1) \times 100, \ i \in \{2,3\} \qquad (1)$$

Where:

$Case_i$ = Case 2 or Case 3
$Case_1$ = Case 1
V = Percentage variation (%)

A. Vehicular Results

A.1. Average Vehicular Delay

This section presents the results corresponding to the vehicular performance of the intersection, primarily evaluated through the average delay per vehicle, which is the main indicator for operational efficiency analysis.

In Case 1, the recorded average delay was 380.93 s/veh, reflecting an operation characterized by frequent interruptions in traffic flow and limited discharge capacity during the analysis period.

In Case 2, the average delay increased to 674.08 s/veh, representing a 76.96% increase compared to Case 1. This result indicates that geometric redesign alone, without modifications to signal control, leads to higher vehicular delays due to lane reorganization and the persistence of operational interferences.

In contrast, Case 3 showed an average delay of 105.60 s/veh, corresponding to a 72.28% reduction compared to Case 1. This decrease highlights the effect of adaptive traffic signal control on improving traffic flow continuity by dynamically redistributing green times based on observed demand.

The results of average vehicular delay are presented in Table IV.

TABLE IV. AVERAGE VEHICULAR DELAY IN THE THREE EVALUATED CASES

No. of Simulations	Average Delay (s)	Percentage Variation with respect to Scenario 1 (%)
Case 1	380.93	-
Case 2	674.08	+76.96 %
Case 3	105.60	-72.28 %

A.2. Number of Stops per Vehicle

The number of stops per vehicle allows evaluation of the level of interruption experienced by vehicles while traveling through the intersection.

In Case 1, an average of 11.47 stops per vehicle was recorded, confirming a highly fragmented traffic operation.

In Case 2, the number of stops increased to 14.99 stops per vehicle, representing a 30.69% increase compared to Case 1. This result is consistent with the observed increase in vehicular delay and suggests that geometric reorganization alone, without adjustments to signal control logic, intensifies flow interruptions.

In contrast, in Case 3, the average number of stops decreased to 4.16 stops per vehicle, corresponding to a 63.73% reduction compared to Case 1. This reduction reflects a more continuous traffic operation, associated with the dynamic prioritization of signal phases based on vehicular demand.

The number of stops per vehicle is summarized in Table V.

TABLE V. NUMBER OF STOPS PER VEHICLE IN THE THREE ANALYZED CASES

No. of Simulations	Average Stops per Vehicle	Percentage Variation with respect to Scenario 1 (%)
Case 1	11.47	-
Case 2	14.99	+ 30.69 %
Case 3	4.16	- 63.73 %

B. Pedestrian Results

B.1. Pedestrian Delay

Pedestrian performance was evaluated using the average pedestrian delay, which in the microsimulation model represents the level of interference experienced by pedestrians before crossing. Although the absolute values of this indicator are low, its relevance lies in the relative comparison among the analyzed cases.

In Case 1, the average pedestrian delay was 0.02 s/ped, reflecting the presence of recurring interruptions during crossing due to the coexistence of vehicular and pedestrian flows without efficient temporal allocation.

In Case 2, pedestrian delay remained at 0.02 s/ped, indicating that geometric redesign alone, without changes in signal

control, does not produce a significant variation in this indicator.
In Case 3, pedestrian delay decreased to values close to zero, representing a reduction of more than 50% compared to Case 1. This decrease reflects reduced interference during crossing, attributable to the dynamic prioritization of pedestrians through adaptive signal control.
The average pedestrian delay is presented in Table VI.

TABLE VI. AVERAGE PEDESTRIAN DELAY IN THE THREE ANALYZED CASES

No. of Simulations	Average Waiting Time (s)	Percentage Variation with respect to Scenario 1 (%)
Case 1	0.02	-
Case 2	0.02	0.00%
Case 3	0.01	− 50%

Note: Although the absolute value of this indicator is low, in microsimulation it represents the pre-crossing interference time; therefore, the relative comparison between scenarios is relevant.

B.2. Pedestrian Accumulation at the End of the Cycle

Pedestrian accumulation at the end of the signal cycle allows evaluation of the discharge capacity of the pedestrian crossing during the analysis period.
In Case 1, an accumulation of 266 pedestrians was recorded, indicating a limited capacity to discharge pedestrian flow.
In Case 2, accumulation decreased to 211 pedestrians, representing an approximate 20.68% reduction compared to Case 1. This reduction is mainly associated with pedestrian channelization and the relocation of crossings, although without a significant change in the temporal allocation of crossing time.
In Case 3, accumulation at the end of the cycle was reduced to 6 pedestrians, corresponding to a decrease of nearly 98% compared to Case 1. This result indicates an almost complete evacuation of pedestrian flow during each signal cycle, attributable to the dynamic prioritization of pedestrian crossings.
Pedestrian accumulation at the end of the cycle is summarized in Table VII.

TABLE VII. PEDESTRIAN ACCUMULATION AT THE END OF THE CYCLE IN THE THREE ANALYZED CASES

No. of Simulations	Active Pedestrians at the End of the Cycle	Percentage Variation with respect to Scenario 1 (%)
Case 1	266	-
Case 2	211	- 20.68 %
Case 3	6	- 97.74 %

B.3. Pedestrian Flow and Speed

In terms of pedestrian flow, Case 1 showed an average value of 0.02 ped/s, associated with slow movement and frequent interruptions.
In Case 2, pedestrian flow increased to 0.03 ped/s, reflecting a moderate improvement due to geometric reorganization of the crossing.
Case 3 recorded the highest pedestrian flow value, with 0.04 ped/s, doubling the value observed in Case 1. This increase indicates greater continuity in pedestrian movement and more efficient use of crossing space.
Additionally, the average pedestrian speed increased from 2.68 km/h in Case 1 to 3.21 km/h in Case 3, confirming a more efficient operation during the crossing phase.
Pedestrian flow and speed are presented in Table VIII.

TABLE VIII. AVERAGE PEDESTRIAN SPEED IN THE THREE ANALYZED CASES

No. of Simulations	Average Pedestrian Speed (km/h)	Percentage Variation with respect to Scenario 1 (%)
Case 1	2.68	-
Case 2	2.45	- 8.58 %
Case 3	3.21	+ 19.78 %

C. Evolution of Conflicts Across Scenarios

The analysis of the evolution of pedestrian–vehicle conflicts allowed identifying clear differences in interaction dynamics as the evaluated interventions were implemented.
In Case 1, a high frequency of conflicts was observed, mainly associated with informal pedestrian crossings outside designated crosswalks, as well as vehicular interferences caused by public transport stops located near the intersection. Additionally, turning maneuvers of large vehicles generated partial lane blockages, increasing delay and reducing traffic flow continuity.
In Case 2, pedestrian channelization and relocation of crossings reduced conflicts associated with informal crossings. However, due to the fixed-time signal control scheme, vehicular conflicts related to accumulation and prolonged stops persisted, particularly at high-demand approaches and during turning movements.
In Case 3, the implementation of adaptive traffic signal control enabled a simultaneous reduction of both pedestrian and vehicular conflicts. The dynamic redistribution of green times reduced interference during crossing, as well as blockages caused by public transport stops and turning maneuvers, resulting in a more orderly intersection operation.
Overall, the observed evolution confirms that geometric redesign contributes to reducing specific conflicts, while adaptive signal control plays a decisive role in reducing the overall magnitude of interactions between users.

CONCLUSIONS

1. The results of the study indicate that adaptive traffic signal control, when applied to urban intersections with high pedestrian–vehicle interaction, significantly reduces vehicular delay and the number of stops per vehicle compared to fixed-time control schemes. In the analyzed case, Case 3 showed substantial reductions in vehicular

delay relative to Case 1, reflecting a more continuous traffic flow operation.

2. Geometric redesign alone (Case 2) contributes to organizing pedestrian flows and reducing conflicts associated with informal crossings; however, under a fixed-time signal control scheme, this type of intervention does not significantly reduce vehicular or pedestrian delay and may even increase it due to the reorganization of lanes and approaches.
3. From a pedestrian perspective, the incorporation of adaptive traffic signal control is crucial for improving flow evacuation during each signal cycle. Pedestrian accumulation at the end of the cycle was drastically reduced in Case 3, from high values in Case 1 to near-zero levels, indicating a more efficient allocation of crossing time for vulnerable users.
4. Conflict analysis revealed that the main critical points at the intersection are associated with informal pedestrian crossings, public transport stops near the crossing area, and turning maneuvers of large vehicles. The combination of geometric redesign and adaptive signal control simultaneously reduces these types of conflicts by minimizing interference between pedestrian and vehicular trajectories.
5. The results confirm that improvements in intersection performance do not rely solely on physical modifications, but on the integration of infrastructure and intelligent control systems.
6. Adaptive traffic signal control allows more efficient use of existing infrastructure without requiring large-scale geometric interventions.
7. Finally, the implementation of this type of system is recommended for intersections with similar characteristics, particularly those located in urban environments with high pedestrian demand and the presence of informal crossings. Future studies may incorporate broader temporal variations, sensitivity analysis of adaptive control parameters, and the evaluation of environmental indicators to extend the scope of the analysis.

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