

Assessment of an Adaptive Traffic Signal System Based on Vehicle-Pedestrian Conflicts at Intersections with High Vehicular and Pedestrian Demand

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Keywords— Adaptive signal control, conflict detection, road safety, traffic simulation, urban intersections.

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I. INTRODUCCIÓN

In many Latin American cities marked by accelerated and poorly planned urban growth, intersections of high vehicular and pedestrian density have become critical points of conflict. These spaces, especially during rush hour, show a risky interaction between turning vehicles and pedestrians crossing, generating delays, dangerous maneuvers and an unsafe road environment. One of the main factors that maintains this problem is the dependence on fixed-time traffic light systems, which don't respond to real traffic conditions. These inflexible systems don't distinguish between times of high or low demand, allowing traffic light phases that coincide in time for pedestrians and vehicular turns, increasing the probability of collisions or dangerous interactions.

Although some systems have evolved towards actuated traffic lights, which detect the presence of vehicles to adjust the duration of the phases, this approach is mainly focused on

optimizing the fluidity of motorized traffic. However, it ignores the dynamics of vehicle-pedestrian conflicts, as it does not incorporate sensors or algorithms capable of detecting their occurrence or adjusting cycles according to pedestrian risk. As a result, vulnerable road users continue to face unsafe environments, and road safety at urban intersections continues to be neglected in the face of decongestion goals.

Solutions to the vehicle-pedestrian conflict have evolved from basic settings to intelligent control systems. In [1], traffic light timers have been observed to induce hasty decisions in drivers, which increases the risk of collision. In addition, turns without protected phases remain a critical source of danger to pedestrians, as many drivers fail to yield the right-of-way [2]. On the other hand, secondary conflicts have been identified when pedestrians are still crossing while vehicles are restarting their journey [3], aggravated by speed and angle of impact, which directly influence the severity of injuries [4]. Likewise, microsimulation techniques combined with the SSAM model have made it possible to detect conflicts not evident in conventional observations [5]. More recently, [6] developed a real-time monitoring system with computer vision and neural networks to track vehicles more accurately, while [7] applied reinforcement learning algorithms to dynamically adjust traffic light cycles. Computer vision has also been incorporated to adapt the phases according to the combined load of pedestrians and vehicles [8]. At the local level, it has been possible to reduce conflicts by up to 80% through simulations with VISSIM and traffic light reprogramming [9], and the installation of sensors at key intersections has improved both crossing times and road safety [10].

Although these studies represent progress, most prioritize vehicular fluidity, without directly considering the detection of vehicle-pedestrian conflicts as a key criterion for adjusting the traffic light phases.

In this context, this study evaluates the effectiveness of an adaptive traffic light system whose control logic is based on the number of conflicts detected between vehicles and pedestrians in real time. The intersection analyzed presents a high level of interaction between vehicular and pedestrian flows, particularly in conflicting turns. inglés

The simulation model was developed in the VISSIM software, while the control logic was programmed using VISVAP, configuring intelligent detectors capable of simultaneously identifying the presence of pedestrians and vehicles in critical crossing areas. The system dynamically adjusts the times of the traffic light phases based on the number of conflicts observed, prioritizing pedestrian safety without significantly compromising the efficiency of vehicular flow. The results obtained show a significant reduction in both the number of conflicts and the average delay times, which validates the effectiveness of the approach based on real conflicts as an adaptive control criterion. This methodology is replicable in other urban intersections with similar characteristics.

II. TOOLS AND METHOD

A. Tools

For the development of this research, a strategic combination of advanced technological tools and rigorous methodological approaches was used, aimed at comprehensively analyzing the effectiveness of an adaptive traffic light system based on the number of conflicts between vehicles and pedestrians, in complex urban environments characterized by a high interaction between vehicular and pedestrian flows. The study was carried out in comparison with scenarios with fixed traffic light systems and with traditional adaptive systems based only on vehicular and pedestrian flows, in order to determine which of these approaches offers better results in terms of both safety and operational efficiency.

First, the **PTV Vissim** micro simulation software was used, a widely validated tool in the field of transport engineering, which allowed the geometry and operational dynamics of the selected intersection to be accurately modelled. Through this platform, different operation scenarios were simulated, considering three traffic light control schemes: fixed system, adaptive system based on vehicular flow, and adaptive system based on vehicle-pedestrian conflicts.

Additionally, a specific model was developed aimed at exporting trajectories to the SSAM security analysis environment. Since this tool only allows the detection of conflicts between vehicles, it was necessary to implement a methodological artifice consisting of modeling pedestrians as vehicular entities with kinematic parameters equivalent to their real behavior (low speed, low dimensions, and defined trajectories in crossing zones). This adaptation made it possible to indirectly represent the vehicle-pedestrian interactions within the SSAM environment, making it possible to quantify them under a consistent approach.

Based on the Vissim environment, the **VisVAP** programming module was integrated, which allowed the development of the control logic of the proposed adaptive traffic light system. Through this environment, the decision-making algorithms that manage traffic light times based on the detection of risk situations between pedestrians and vehicles were coded, which made it possible to simulate a more realistic behavior of the system under conflict conditions.

Subsequently, to assess the impact of the three cases from a road safety point of view, the Surrogate Safety Assessment Model (SSAM), developed by the Federal Highway Administration (FHWA), was used. This tool processed the

trajectory files generated by Vissim, allowing the identification and quantification of conflicts by means of surrogate security indicators. In particular, *Time to Collision* (TTC) was used as the main metric, which measures the time remaining for a potential collision between two users on a convergent trajectory. For the classification of conflicts, TTC thresholds were established according to severity levels: $TTC = 0.0$ s (critical), $TTC \leq 0.5$ s (high), $TTC \leq 1.0$ s (medium) and $TTC \leq 1.5$ s (low). Conflicts were counted based on the identification of events in which two entities (vehicles or pedestrians modeled as vehicles) present conflicting trajectories within these ranges.

It should be noted that the implementation of the artifice in Vissim was fundamental, since SSAM does not natively allow the detection of conflicts between vehicles and pedestrians. Therefore, this methodological adaptation guaranteed the consistency of the analysis and the correct estimation of vehicle-pedestrian conflicts within the simulation framework

Regarding data collection, a specific format was designed for the registration of vehicular and pedestrian capacity. These data were obtained through RPA flights carried out during representative time slots of maximum demand, which guaranteed a reliable input and high spatial-temporal resolution for the calibration of the model. In addition, to estimate the real operating speeds at the intersection, a methodology of direct observation in the field was applied, which consisted of measuring travel times over previously delimited distances for different types of vehicles.

This comprehensive methodological approach allowed not only to evaluate the operational efficiency of the adaptive system, but also to quantify its effect in terms of conflict reduction and improved road safety. Together, the tools used provided a solid technical basis to support the research findings and propose a scalable and replicable solution in other urban intersections with similar risk conditions.

B. Method

The methodology applied in this research followed a quantitative-experimental approach, structured in a logical sequence that allowed for an objective evaluation of the effects of implementing an adaptive traffic signal system based on real-time conflict detection. First, a general analysis of the selected intersection was conducted, considering geometric characteristics, pedestrian and vehicle behavior, existing signage, and the duration of current traffic signal phases. Subsequently, field data collection was carried out, including vehicle and pedestrian counts, travel speeds, and crossing times. This information allowed for the characterization of the current situation and the development of the simulation model.

Once the current scenario was defined, it was modeled in the PTV VISSIM software, calibrating the model parameters based on the collected empirical data.

Next, the two adaptive traffic light systems programmed in the VisVAP environment were designed. One was based on the variation of vehicular and pedestrian flows observed at the intersection. This model, also implemented in the VisVAP environment, established rules that modify traffic light phase timings according to the number of vehicles or pedestrians detected at each approach, adjusting the cycles proportionally to the recorded demand. To achieve this, predefined thresholds for vehicle and pedestrian volume were

established, above which phase extensions or reductions are enabled. While this strategy allows for some operational flexibility in the face of variable demand, it does not consider the level of risk generated by interactions between different road users, which limits its effectiveness in terms of road safety.

The other scenario involves the design of an adaptive traffic signal system based on conflict detection, which is part of the innovative approach proposed in this research. In this system, logical rules were implemented based on the detection of the simultaneous presence of pedestrians and vehicles in areas of potential conflict. The system dynamically prioritizes pedestrian crossings based on the detected risk, without causing prolonged disruptions to traffic flow, thus ensuring a balance between safety and operational efficiency.

The three scenarios were modeled and simulated under homogeneous input conditions using PTV VISSIM software to ensure comparability. Subsequently, the trajectory data generated by each simulation were processed using the Surrogate Safety Assessment Model (SSAM), a tool that allowed for the identification and quantification of road safety conflicts without the need to observe actual accidents. The analysis included the detection of near-intersections, sudden braking, aggressive lane changes, and other evasive maneuvers that represent latent risks for road users. This model was incorporated as the third scenario evaluated, following the traditional fixed traffic light system and the adaptive flow model.

Finally, a comparative evaluation of these three traffic signal systems was conducted using quantitative indicators such as the total number of recorded conflicts, the frequency of critical user interactions, and average crossing times for both pedestrians and vehicles. The results showed that the conflict-based adaptive traffic signal system performed best overall, achieving a significant reduction in safety conflicts and operational improvements compared to the other two approaches. These findings demonstrate that a control logic based on real-time risk detection offers a more effective and safer alternative for managing mobility at highly complex urban intersections. Figure 1 shows the diagram illustrating the stages of the procedure for designing and analyzing the three scenarios.

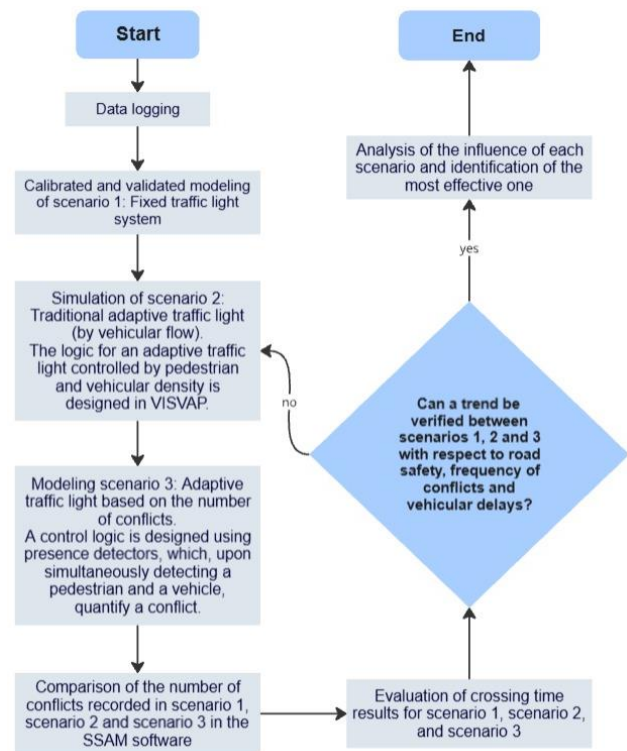


Fig. 1. Procedure of the method to design and analyze the three scenarios.

III. RESULTS AND ANALYSIS

A. Results

To evaluate the effectiveness of different traffic signal control systems at urban intersections with high vehicular and pedestrian demand, the results focus on three key indicators: number of conflicts, crossing time, and vehicular flow per approach. The simulation was conducted over a period of 600 to 4,200 seconds, including an initial warm-up period to eliminate transient effects and ensure the representativeness of the results.

Additionally, 15 independent replicates of the model were run, using a fixed random seed (value 25), with the aim of ensuring statistical consistency and reproducibility of the results obtained.

1) Scenario 1 - Fixed Traffic Light::

This scenario represents the actual condition at the intersection under study. Its modeling used data collected in the field, including vehicle and pedestrian counts, as well as the current traffic light phase schedule. The control system operates under a fixed-time scheme, without the capacity to adapt to variations in demand. This configuration generates a high number of conflicting interactions between vehicles and pedestrians, in addition to long crossing times and variability in traffic flow. Figure 2 shows the plan view corresponding to this baseline situation.

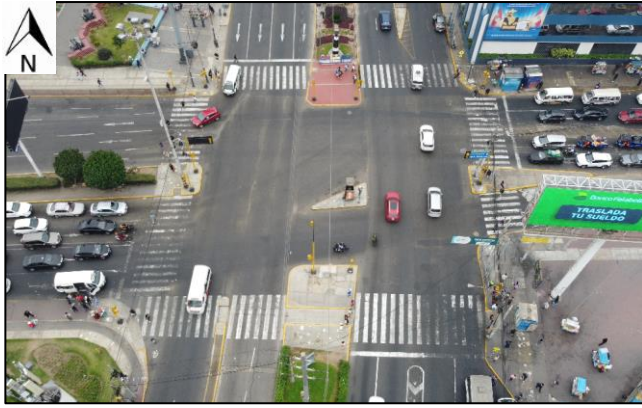


Fig. 2. Plan view of stage 1, current situation..

The results obtained for this scenario are presented in Table I (vehicle-pedestrian conflicts), Table II (average crossing times) and Table III (average vehicular flow per access).

TABLE I. VEHICLE-PEDESTRIAN CONFLICTS AT FIXED TRAFFIC LIGHTS

<i>TTC Range</i>	<i>Quantity</i>	<i>Level of Conflict</i>
$TTC = 0.0$	919	Critical
$TTC \leq 0.5$	199	High
$TTC \leq 1.0$	401	Medium
$TTC \leq 1.5$	685	Low
Total	2,204	—

TABLE II. AVERAGE VEHICULAR CROSSING TIME PER ACCESS – FIXED TRAFFIC LIGHTS

<i>Access</i>	<i>Average time (s)</i>
North-South	7.26
South-North	7.18
East-West	8.48
West-North	10.13
Average	8.26

TABLE III. AVERAGE VEHICULAR FLOW PER ACCESS – FIXED TRAFFIC LIGHTS (VEH/ACCESS/H)

<i>Access</i>	<i>Vehicles/access/time</i>
North	2,328
South	2,484
East	572
West	836
Average	1,555

2) Scenario y 2 - Traditional Adaptive Traffic Signal (by traffic flow):

This scenario corresponds to a conventional adaptive system widely used in urban traffic management, in which traffic signal phase times are adjusted based on the volume of vehicles detected at each approach. Its inclusion in the study stems from the need to evaluate whether this type of control, primarily focused on vehicle efficiency, also contributes to reducing vehicle-pedestrian conflicts. While this approach

improves traffic flow and reduces crossing times, it does not explicitly consider pedestrian interaction or risk, so conflict levels remain relatively high.

The results for this scenario are shown in Table IV (vehicle-pedestrian conflicts), Table V (average crossing times), and Table VI (average traffic flow per approach).

TABLE IV. CONFLICTOS VEHÍCULO-PEATÓN EN SEMAFORIZACIÓN ADAPTATIVA POR VEHICLE-PEDESTRIAN CONFLICTS IN ADAPTIVE FLOW TRAFFIC SIGNALS

<i>TTC Range</i>	<i>Quantity</i>	<i>Level of Conflict</i>
$TTC = 0.0$	650	Critical
$TTC \leq 0.5$	150	High
$TTC \leq 1.0$	360	Medium
$TTC \leq 1.5$	610	Low
Total	1,770	—

TABLE V. AVERAGE VEHICLE CROSSING TIME – ADAPTIVE TRAFFIC SIGNALS BY FLOW

<i>Access</i>	<i>Average time (s)</i>
North-South	6.89
South-North	6.92
East-West	8.1
West-North	9.51
Average	7.86

TABLE VI. AVERAGE VEHICULAR FLOW PER ACCESS – ADAPTIVE TRAFFIC SIGNALS BY FLOW (VEH/ACCESS/H)

<i>Access</i>	<i>Vehicles/access/time</i>
North	2,360
South	2,530
East	580
West	850
Average	1,580

3) Scenario 3 - Adaptive Traffic Signal Based on the Number of Conflicts:

This scenario corresponds to the model proposed in the research, which introduces a control logic based on the detection of potential conflicts between vehicles and pedestrians. The system dynamically adjusts the traffic signal phases based on the simultaneous presence of both users in critical areas, prioritizing pedestrian safety without significantly impacting vehicle efficiency. Figure 3 shows the location of the vehicle and pedestrian presence detectors implemented at the intersection, as well as the three traffic signal operation phases designed to regulate movements safely and orderly. Figure 4 shows the phase diagram corresponding to the proposed system.

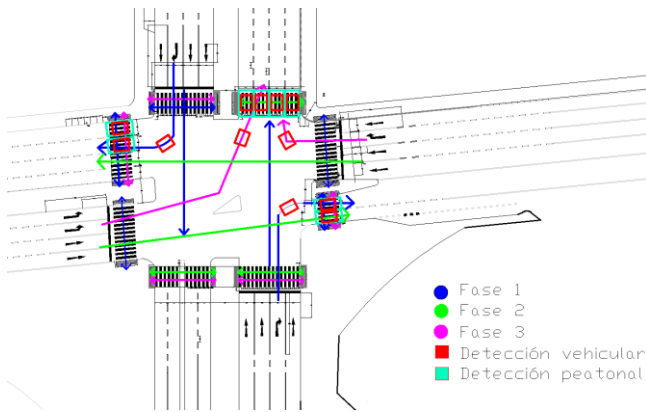


Fig. 3. Location of vehicle and pedestrian detectors and traffic light phases of the intersection

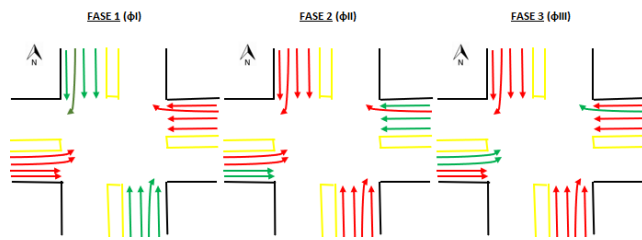


Fig. 4. Phase diagram of scenario 3

For this scenario, Table VII presents the identified vehicle-pedestrian conflicts, while Table VIII and Table IX show the average crossing times and the average vehicular flow per access, respectively.

TABLE VII. VEHICLE-PEDESTRIAN CONFLICTS IN CONFLICT-BASED ADAPTIVE TRAFFIC SIGNALS

<i>TTC Range</i>	<i>Quantity</i>	<i>Level of Conflict</i>
$TTC = 0.0$	420	Crítico
$TTC \leq 0.5$	120	Alto
$TTC \leq 1.0$	220	Medio
$TTC \leq 1.5$	321	Bajo
Total	1,081	—

TABLE VIII. AVERAGE VEHICLE CROSSING TIME – ADAPTIVE TRAFFIC SIGNALS BASED ON CONFLICTS

<i>Access</i>	<i>Average time (s)</i>
North-South	6.88
South-North	6.95
East-West	8.29
West-North	9.72
Average	7.96

TABLE IX. AVERAGE VEHICULAR FLOW PER ACCESS – ADAPTIVE TRAFFIC SIGNALS BASED ON CONFLICTS (VEH/ACCESS/H)

<i>Access</i>	<i>Vehicles/access/time</i>
North	2,234
South	2,411
East	544
West	796

<i>Access</i>	<i>Vehicles/access/time</i>
Average	1,496

B. Analysis and Interpretation

In order to comparatively evaluate the performance of the three scenarios with traffic light control systems, the results are summarized in Tables X, XI, and XII, which present the main safety and operational efficiency indicators: total number of conflicts, average crossing time, and vehicle flow per lane.

TABLE X. COMPARISON OF THE TOTAL NUMBER OF VEHICLE-PEDESTRIAN CONFLICTS

<i>Scenario</i>	<i>Total Conflicts</i>
Fixed traffic light	2204
Traditional adaptive traffic light	1770
Conflict-based adaptive traffic light	1081

TABLE XI. COMPARISON OF AVERAGE VEHICLE CROSSING TIME

<i>Scenario</i>	<i>Average Time (s)</i>
Fixed traffic light	8.26
Traditional adaptive traffic light	7.86
Conflict-based adaptive traffic light	7.96

TABLE XII. COMPARISON OF AVERAGE VEHICULAR FLOW BY ACCESS

<i>Scenario</i>	<i>Vehicle Flow (Veh/access/h)</i>
Fixed traffic light	1,555
Traditional adaptive traffic light	1,580
Conflict-based adaptive traffic light	1,496

The results show clear differences between the three traffic light control schemes. Fixed traffic lights (scenario 1) showed the worst performance, with the highest number of conflicts (2204), longest crossing times (8.26 s) and a flow of 1555 vehicles/access/h, reflecting a rigid and inefficient operation.

The adaptive flow system (scenario 2) improved operational efficiency, achieving the lowest crossing time (7.86 s) and the highest flow (1580 veh/access/h); however, it maintained high levels of conflict (1770), as it did not consider the vehicle-pedestrian interaction.

In contrast, the conflict-based adaptive system (scenario 3) showed the best overall performance, reducing conflicts to 1081 (–50.9% compared to the baseline scenario) while maintaining adequate crossing times (7.96 s) and traffic flow (1496 veh/access/h). This demonstrates that the proposed approach significantly improves safety without compromising efficiency, positioning itself as a balanced and replicable solution for high-demand urban intersections.

IV. VALIDATION

Before validating the results, the baseline model corresponding to the current state (scenario 1) was calibrated using data collected in the field. This process was carried out in PTV VISSIM by adjusting the parameters of the Wiedemann 74 tracking model, including the desired distance, acceleration sensitivity, and driver reaction time (Fig. 5). The parameters were adjusted iteratively until the model adequately reproduced the conditions observed at the intersection.

Car following model

Wiedemann 74

Model parameters

Average standstill distance:

Additive part of safety distance:

Multiplic. part of safety distance:

Fig. 5. Wiedemann 74 parameters.

Following calibration, a second data collection was conducted in the field to validate the adjusted baseline model. From these new records, statistical validation was applied using the StatKey tool, employing a bootstrap-based mean difference test. The analysis was performed separately for each access point at the intersection, comparing the crossing times observed in the field with those obtained through simulation. In all cases, the differences were not statistically significant, confirming that the calibrated model accurately represents real-world conditions. One of the results of the statistical analysis is shown in Figure 6.

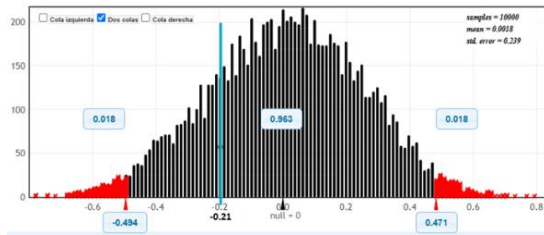


Fig. 6. Validación estadística con StatKey del Acceso Norte-Sur.

Finally, to verify the contribution of the adaptive system based on conflict detection, a comparative analysis between models was performed using StatKey. The results of scenario 1 (fixed traffic lights) were statistically compared to those of scenario 2 (adaptive by vehicular flow) and scenario 3 (adaptive by conflict), using two key indicators: average crossing time and total number of vehicle-pedestrian conflicts.

Figures 7 and 8 show the validation of each scenario with respect to the average crossing time per access point. Table XIII shows a summary of the crossing time for each case, and Table XIV shows a summary table of the mean differences (averages) and p-values.

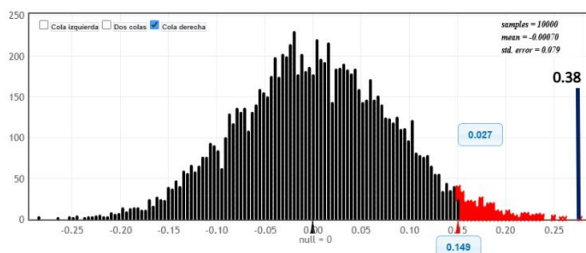


Fig. 7. Validation of scenario 2 with respect to the North-South Access Crossing Times.

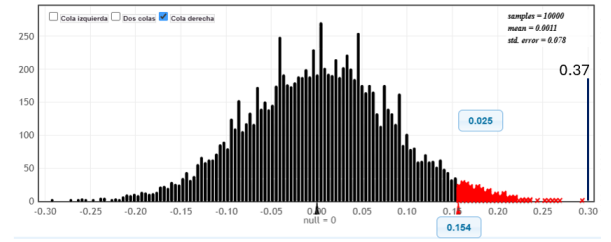


Fig. 8. Validation of scenario 3 with respect to the North-South Access Crossing Times.

TABLE XIII. SUMMARY OF CROSSING TIME FOR EACH SCENARIO (Sc) PER ACCESS

Access	Sc. 1 Current (s)	Sc. 2 (s)	Sc. 3 (s)
North-South	7.26	6.89	6.88
South-North	7.18	6.92	6.95
East-West	8.48	8.10	8.29
West-North	10.13	9.51	9.72
Average	8.26	7.86	7.96

TABLE XIV. COMPARISON OF THE MEANS, WITH RESPECT TO CROSSING TIMES

Access	Difference (s) (1 vs 2)	Difference (s) (1 vs 3)
N-S	0.38	0.37
S-N	0.23	0.26
E-W	0.38	0.19
W-N	0.62	0.41

Figures 9 and 10 show the validation of each scenario with respect to the number of vehicle-pedestrian conflicts. Table XV shows the summary of the number of vehicle-pedestrian conflicts for each case, and Table XVI shows the summary table of mean differences (averages) and p values.

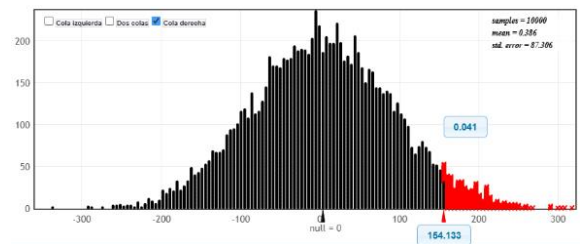


Fig. 9. Validation of scenario 2 with respect to the number of vehicle-pedestrian conflicts.

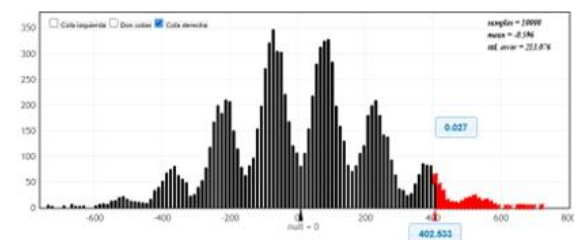


Fig. 10. Validation of scenario 3 with respect to the number of vehicle-pedestrian conflicts.

TABLE XV. SUMMARY OF CONFLICTS FOR EACH SCENARIO

Scenario	Total number of conflicts
Scenario 1 (Current)	2204
Scenario 2 (Adaptive by flow)	1770
Scenario 3 (Adaptive by conflict)	1081

TABLE XVI. COMPARISON OF AVERAGE AND % IMPROVEMENT, WITH RESPECT TO CONFLICTS

Comparison	Total conflict difference	%
1 vs 2	434	19.70
1 vs 3	1123	50.90

Scenario 3 showed the greatest improvement, with a 50.9% reduction in conflicts (from 2204 to 1081), while maintaining adequate crossing times (7.96 s). These differences were statistically significant ($p < 0.05$), confirming the effectiveness of the proposed model.

V. CONCLUSIONS

The research demonstrates that an adaptive traffic signal system based on vehicle-pedestrian conflict detection is an effective alternative for controlling high-demand urban intersections. Through simulations in PTV VISSIM, with logic implemented in VISVAP and evaluation in SSAM, it was shown that this approach responds better to real-world user interactions, significantly reducing risks without compromising traffic flow.

Compared to fixed traffic lights, the proposed model (Scenario 3) achieved a 50.9% reduction in conflicts (from 2204 to 1081), while maintaining adequate crossing times (7.96 s) and an acceptable average traffic flow per access point (1496 vehicles/access/h). This confirms the limitations of rigid systems in the face of dynamic demand conditions.

Regarding the flow-adaptive system (Scenario 2), although it exhibits the highest performance in vehicle efficiency, it does not significantly reduce conflicts. In contrast, the conflict-based model incorporates risk as a control variable, achieving a better balance between safety and efficiency.

Finally, statistical validation confirmed that the observed improvements are significant ($p < 0.05$), supporting the model's reliability. Therefore, the proposed methodology is replicable and scalable, representing a relevant contribution to

the development of safer traffic control systems focused on vulnerable road users.

RECOGNITIONS

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