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Calibration of a Mesoscopic Simulation Model for the Optimization of Traffic Performance Parameters in a Commercial District

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Abstract: Traffic congestion in urban commercial districts presents a critical challenge to sustainable mobility, particularly in developing cities. This study addresses this issue by developing and calibrating a mesoscopic simulation model to optimize traffic performance parameters in the commercial district of Ayacucho, Peru. The methodology was based on extensive fieldwork to gather traffic volume, travel time, and parking data. Using this data, a PTV Vissim model was developed and rigorously calibrated, with its accuracy validated through the Geoffrey E. Havers (GEH) statistic. Various traffic management strategies, including signal timing adjustments and parking supply regulation, were simulated and evaluated. The results indicate a substantial improvement in network performance: Average intersection delay was reduced from 10.72 seconds to 7.40 seconds, and a significant decrease in queue lengths was observed. The findings confirm that calibrated mesoscopic simulation serves as a robust and effective tool for quantitatively assessing traffic interventions, thereby providing municipal authorities with reliable data for evidence-based urban planning.

Keywords: Mesoscopic simulation; Model calibration; Traffic congestion; Traffic performance metrics; Parking management; PTV Vissim

1 Introduction

Urban vehicular traffic represents one of the most critical challenges facing developing cities, with economic losses exceeding $87 billion annually at the global level [1]. Commercial areas, as nerve centers of economic activity, generate complex traffic patterns due to the convergence of private vehicles, public transport, pedestrians, and commercial activities, creating bottlenecks that extend beyond their immediate perimeter [2].

In Peru, intermediate cities such as Ayacucho face exponential growth in their automotive fleet, with an annual increase of 8.2% at the national level [3]. The Nery García Zarate market, which functions as the main wholesale and retail distribution center for Huamanga city, exemplifies this challenge, experiencing congestion that affects approximately a 2–3 block radius during peak hours, resulting in estimated economic losses and air quality deterioration.

Traditional traffic management approaches in Latin American contexts have shown limited effectiveness due to aggressive driving behaviors, inadequate infrastructure, and insufficient regulatory enforcement [4]. Recent advances in traffic microsimulation, particularly mesoscopic modeling using PTV Vissim, offer promising alternatives for analyzing complex urban scenarios and evaluating regulatory interventions before implementation [5, 6].

Existing literature addresses market-area traffic management primarily in developed countries [7], with limited research focused on Latin American intermediate cities with specific characteristics: mixed vehicle types (motorcycles, mototaxis, buses), informal street commerce, and limited parking infrastructure. Vehicular flow parameters on multilane highways require specific calibration for local conditions [8], while queue length estimation at signalized intersections demands adaptive models that consider the characteristic vehicle-following behavior of each region [9, 10].

This study addresses this gap by developing a mesoscopic traffic model calibrated for the Nery García Zarate market area. The selection of PTV Vissim over alternatives (AIMSUN, SUMO, CORSIM) was based on its superior handling of mixed traffic conditions, robust calibration capabilities using GEH statistics, and proven performance in similar Latin American contexts [11].

2 Related Work

2.1 Traffic Microsimulation in Complex Urban Areas

Traffic microsimulation modeling has evolved significantly to address complex urban environments with multiple vehicle types and heterogeneous traffic patterns. Pinedo et al. [1] developed comprehensive strategies for vehicular conflict reduction in urban areas with high commercial activity, using PTV Vissim simulation models to achieve 32% reductions in total conflicts and 49% reductions in high-risk conflicts through coordinated implementation of actuated traffic signals and road infrastructure modifications.

Wang et al. [2] investigated simulation techniques for regional traffic analysis in urban renewal contexts, employing macroscopic fundamental diagram theory and urban traffic microcirculation. Their results demonstrated 13.29% reductions in average vehicle operation time and 19.20% improvements in regional traffic operation efficiency, establishing replicable methodologies for cities undergoing modernization.

Kučera and Chocholač [12] designed specialized urban logistics simulation models using PTV VISSIM, focusing on traffic infrastructure planning optimization at critical intersections. Lin et al. [13] developed comparative analyses of road organization in central business districts, demonstrating that one-way street system implementation produces superior performance compared to traditional bidirectional configurations.

2.2 Advanced Calibration and Parameter Optimization Methodologies

Precise calibration of microsimulation models requires sophisticated methodologies that consider local driving behavior particularities. Gunarathne et al. [4] developed optimization techniques using genetic algorithms for VISSIM driver behavior parameter calibration, specifically adapted for heterogeneous traffic conditions in developing countries such as Sri Lanka. Their methodology demonstrated superior effectiveness for multi-branch intersections in environments with aggressive driving behavior.

Arafat et al. [7] introduced data-driven approaches for microsimulation model calibration, using degree of saturation at signalized intersections as a fundamental variable. Their methodology incorporates real-world vehicle trajectory data to determine optimal car-following parameter values, demonstrating that VISSIM can be effectively calibrated using non-binary attributes incorporated in the software.

Gao et al. [14] proposed innovative methods to improve calibration model accuracy and interpretability, developing three novel techniques that optimize both global and local parameters. Their results confirmed that dual calibration produces greater consistency with real driving characteristics compared to traditional single calibration approaches.

Otkovic et al. [15] validated calibration methodologies for microsimulation models using neural networks in the urban transport network of Osijek, Croatia. Their validation procedure on other intersections within the same transport network demonstrated satisfactory correspondence with real traffic conditions measured in the field.

2.3 Vehicle Behavior Modeling and Heterogeneous Traffic

Precise modeling of vehicular behavior under mixed traffic conditions represents one of the most significant challenges in urban microsimulation. Raju et al. [10] developed specialized methodologies for vehicle-following behavior modeling using trajectory data under non-lane-based mixed traffic conditions. Their research identified hysteresis phenomena in leader-follower behavior, providing improved calibration for psychophysical car-following models.

Priya and Ramadurai [16] investigated VISSIM-specific calibration for heterogeneous traffic conditions in Indian contexts, developing statistical methods that incorporate neural networks for parameter optimization. Their approach identified critical driver behavior parameters for each vehicle type through comprehensive sensitivity analysis.

Maheshwary et al. [17] established calibration methodologies for microsimulators in urban heterogeneous traffic operations, using vehicle class-specific linear regression models and genetic algorithm-based optimization to obtain optimal parameter values differentiated by vehicle type.

2.4 Applications in Developing Countries and Validation

Microsimulation applications in developing countries require specific methodological adaptations considering limited infrastructure, characteristic driving behavior, and non-conventional vehicle types. Bore and Ambunda [18] conducted microscopic evaluations of traffic operations on urban arterial roads in Namibia, using PTV VISSIM microsimulation techniques to demonstrate substantial reductions in vehicle delays through optimized signal control implementation.

Ranpura et al. [19] developed calibration methodologies for mixed traffic microsimulation models specifically for signalized intersections in Indian cities. Their research identified eight critical sensitive parameters affecting effectiveness measures, using genetic algorithms for optimization with 95% confidence levels.

2.5 Road Safety Studies and Impact Analysis

Integration of road safety analysis into microsimulation models enables comprehensive evaluations of traffic interventions. Hussain et al. [20] developed integrated VISSIM-SSAM approaches for pedestrian crash prediction and mitigation at urban crossings, achieving precise calibration and validation that facilitates evaluation of multiple intersection control scenarios.

Qiu et al. [21] evaluated traffic and safety impacts of diverging diamond interchanges through detailed microsimulation studies, revealing 55% reductions in average delays and 36% increases in average speeds compared to traditional roundabout configurations.

Chawla et al. [22] developed integrated modeling approaches for exhaust emission evaluation in urban road networks, proposing specific correction factors for vehicles operating under heterogeneous conditions typical of developing nations, establishing significant correlations between vehicle duration on links and emission generation.

2.6 Specific Parameter Analysis and Advanced Modeling

Detailed analysis of specific traffic parameters requires specialized methodologies for different road configurations. Haq et al. [6] investigated passing sight distance estimation for truck platoons using VISSIM calibration and validation, developing mathematical kinematic models to compute necessary passing distances in multiple traffic scenarios with 70 mph speed limits.

Weyland et al. [8] conducted systematic parametric studies on lane flow distribution on multilane freeways using PTV Vissim microscopic simulation. Their research quantified effects of empirically determinable parameters on flow distribution, identifying desired speed distributions, section gradients, and safety distance reduction factors as critical variables.

Abutahoun et al. [9] developed methodologies for queue length estimation in signal control using discrete event simulation, creating models that incorporate stochastic behavior for arrival and departure vehicles following Poisson distributions with exponential inter-arrival times.

2.7 Comparative Analysis and Software Reviews

Al-Msari et al. [5] presented a comprehensive review of artificial intelligence approaches in VISSIM driving behavior simulation. Their analysis examined five important aspects: calibration, driving behavior, incidents, and heterogeneous traffic simulation, as well as artificial intelligence utilization with VISSIM, revealing the most suitable methodological utility adapted to specific research objectives.

Algherbal and Ratrout [23] conducted comparative analysis of currently used microscopic, macroscopic, and mesoscopic traffic simulation software. Their evaluation of ten software options was based on traffic flow models, software availability, output visualization, and intelligent transportation system incorporation, concluding that Vissim, Aimsun, and TransModeler better incorporate ITS and connected autonomous vehicles.

2.8 Research Gap and Contribution

Current literature presents significant limitations in three main areas: (1) insufficient focus on commercial areas of Latin American intermediate cities with specific characteristics of limited infrastructure, aggressive driving behavior, and non-conventional mixed vehicle types, (2) lack of validated methodologies for model calibration incorporating informal vehicles typical of these regions (mototaxis, motorcycles, street vendors) and non-lane-based traffic conditions, and (3) absence of comprehensive evaluation of specific regulatory instruments (parking meters, directional modifications, optimized traffic signals) implemented in a coordinated manner within simulation environments that reflect the socioeconomic and cultural particularities of the Latin American context.

This study addresses these critical gaps through development of a mesoscopic model specifically calibrated for Latin American market environments, incorporating validated GEH statistics-based calibration methodologies adapted to local heterogeneous traffic conditions, and quantitatively evaluating multiple coordinated regulatory interventions through comprehensive simulation scenarios that consider the unique vehicular, pedestrian, and commercial behavior characteristics of the study area in Ayacucho, Peru.

3 Proposed Methodology

3.1 Study Area Definition and Characteristics

As shown in Figure 1, the study area encompasses the commercial district surrounding Nery García Zarate Market in Ayacucho, Peru, located at 2,761 m elevation. The area boundaries were defined based on traffic influence zones and parking demand patterns, bounded on the north by Jr. José Antonio de Sucre and 26 de Enero Avenue, on the south by Nery García Zarate Avenue, on the east by the intersection of Hidalgo Avenue and Los Pinos Avenue, and on the west by José Antonio de Sucre Avenue.

Figure 1. Delimitation of the study area

The modeling approach utilized mesoscopic level analysis, establishing the network around Nery García Zarate market where connectors represent streets for vehicle circulation and nodes represent street intersections. The following morphological parameters were incorporated for detailed road network modeling: roadway width, road length, and flow direction.

Figure 2 illustrates the delimited study area that focuses on roads around the Nery García Zarate market, including Jr. Mariscal Llerena, Jr. José Olaya, Jr. José Antonio de Sucre, Av. Agustín Gamarra, Av. Los Pinos, Av. Nery García Zarate, Jr. Ubilluz, Jr. Condorcunca, located in UTM Zone 18L and Zone L of the UTM Projection South Zone Datum WGS84.

Figure 2. Delimited study area

3.2 Problem Identification and Context Analysis

The problem of vehicular traffic in large cities is well-known and recurring, affecting resident populations and visitors in different parts of the world. Ayacucho, as a growing city needing continuous economic income through its markets, faces inefficient vehicular flow around the Nery García Zarate market, particularly in streets affluent to this commercial establishment.

As observed in Figure 3, this issue is aggravated by street commerce, inadequate use of streets for parking, increased vehicle numbers, lack of enforcement personnel, and limited use of traffic regulation instruments around this important commercial establishment in Ayacucho.

Figure 3. Vehicle traffic at the main gate of the Nery Garcia Zarate market

3.3 Field Data Collection and Traffic Measurements

3.3.1 Peak hour identification and traffic volume data

Figure 4 presents the stacked traffic volumes per 15-minute intervals during the study period. Peak hour data collection focused on the 11:30–12:30 AM period, identified through preliminary 24-hour observations as the maximum vehicular flow period. Peak hour data was obtained from time slots where vehicle numbers average normal standards, working with average ratios to establish information averages.

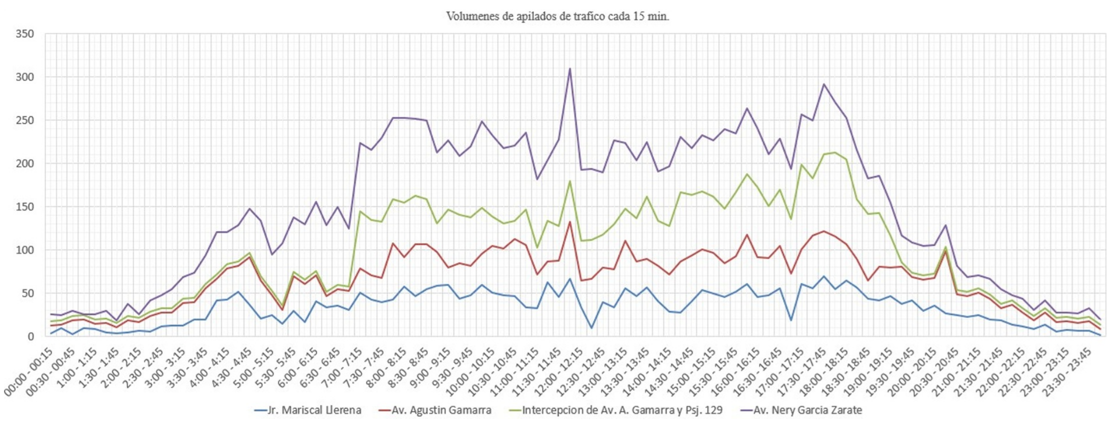

Figure 4. Stacked traffic volumes per 15 minutes

Traffic data collection was conducted during working days (Tuesday to Sunday) to capture representative traffic patterns of common days with higher flow compared to Mondays and Tuesdays. The GEH statistical technique was used to compare vehicular traffic volumes between real data and modeling to guarantee adequate and reliable calibration.

3.3.2 Cordon capacity and parking demand assessment

Comprehensive parking analysis was conducted through cordon counting methodology. Table 1 shows the current parking space supply in the study area. Data collection was performed during gauging, based on counts according to the cordon gauging plan. Eight entry points and eleven exit points were identified, including streets with high traffic volume such as Jr. Mariscal Llerena, Av. Agustín Gamarra, and Pasaje 129, as well as low-traffic streets like Jr. Hidalgo, Pasaje 130, and Jr. Amauta. Table 2 presents the vehicles remaining in the study area during peak periods, with analysis showing that parking space demand at the critical point reaches 113 vehicles, concluding that supply is exceeded by demand of circulating vehicles within the study area by 113 equivalent vehicles seeking parking spaces.

Table 1. Parking space supply

Location	Type	Capacity (vehicles)
Jr. Hidalgo garage	Private	38
Total	-	38

Table 2. Parking space supply

Time	Vehicle Entry	Vehicle Exit	Vehicles Remaining
11:30–11:35	98	63	35
11:35–11:40	97	88	44
11:40–11:45	101	88	57
11:45–11:50	107	98	66
11:50–11:55	86	102	50
11:55–12:00	104	89	65
12:00–12:05	85	80	70
12:05–12:10	85	77	78
12:10–12:15	93	70	101
12:15–12:20	91	88	104
12:20–12:25	87	87	104
12:25–12:30	97	88	113

Note: Analysis shows parking space demand at critical point reaches 113 vehicles, concluding that supply is exceeded by demand of circulating vehicles within the study area by 113 equivalent vehicles seeking parking spaces.

3.4 Physical Infrastructure Assessment and Network Characterization

3.4.1 Roadway width and length measurements

Field work focused on collecting information necessary to define road network characteristics. Each value was verified by direct field measurements, review of topographic area plans, and evaluation of traffic performance.

Field work focused on collecting information necessary to define road network characteristics. Each value was verified by direct field measurements, review of topographic area plans, and evaluation of traffic performance. As shown in Figure 5, roadway width measurements were taken during night hours as roads are heavily congested during most of the day, avoiding obstructions. The dimensions of roadways have not undergone significant variations. Field work measured roadway widths on all roads, with each measurement taken at the middle of each block, ensuring representative average roadway width.

3.4.2 Network block length and flow direction analysis

Network block length was measured considering the central part of intersections making up the streets. Satellite images at appropriate scale were used for modeling purposes. For streets outside the network (entrances and exits), only sufficient lengths were included to perform adequate modeling. Figure 6 depicts the traffic flow directions that were established based on current Provincial Municipality of Huamanga regulations and field inspections. The term "lane" refers to traffic flow on the same road, as physical lane separations are not implemented. Vehicle traffic directions were established based on inspections carried out in the study area.

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Figure 5. Measurement of roadways within the study area

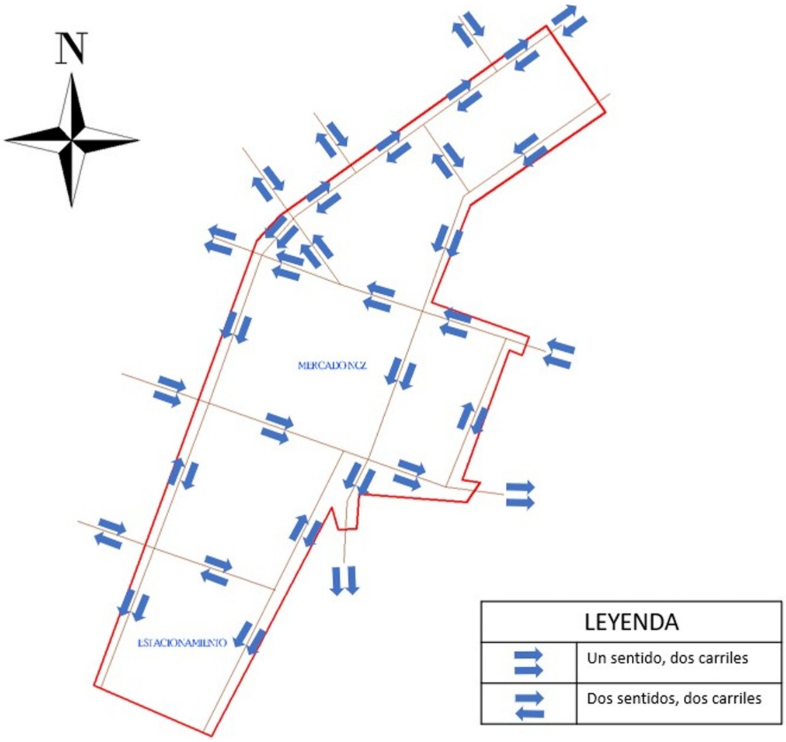

Figure 6. Direction and number of lanes

3.4.3 Road capacity analysis

Road capacity calculation selected sections with highest traffic congestion from the street set, as listed in Table 3, representing entire road lengths. This selection represents the entire length of the road for capacity analysis purposes.

3.5 PTV Vissim Microsimulation Model Development

3.5.1 Software selection and application

PTV Vissim 2024 was selected as the traffic simulation platform due to its comprehensive tools for mixed traffic analysis and mesoscopic modeling capabilities appropriate for the study scale. Vissim is a traffic analysis program for managing road networks, enabling traffic component identification, traffic flow description, and network simulation performance.

The evaluation tools within the simulator allow multiple result types, requiring user configuration to obtain useful results. During configuration, specific variables can be requested or comprehensive evaluation using node options can be implemented. After configuration, simulation runs provide run data requiring processing for final analysis.

Table 3. List of streets with highest observed vehicular traffic

Street Code	Street Name
RT01	Jr. Mariscal Llerena
RT03	Pasaje 129 (NeryG. Zarate)
RT04	Jr. Condorcunca (Cdra. 1)
JAS01	Av. José A. de Sucre (Cdra. 1)
JAS01	Av. José A. de Sucre (Cdra. 4)
JAS01	Av. José A. de Sucre (Cdra. 6)
AG01	Av. Agustín Gamarra (Cdra. 1)

3.5.2 Input volume and network entry points

Vehicle entry points to the study area were determined by demarcating the area of influence of Nery García Zarate Market, incorporating traffic signs indicating street directions. Figure 7 shows the eight entry points that were established and gauged on different days, representative of vehicle numbers and personnel availability. Traffic was measured at 5-minute intervals, accounting for vehicle number differences and direction patterns upon entering the study area. Table 4 presents the vehicle flow within the study area. Note that average gauging was used despite peak hour flow focus, as flow was not homogeneous. Stochastic behavior was assigned in Vissim to behave heterogeneously as in reality.

Figure 7. Entrance of vehicles to the study area

3.5.3 Distribution and route assignment

As illustrated in Figures 8 and 9, route assignment was determined after performing vehicular capacity analysis, specifying street directions and incorporating percentage distribution within the study area. The system was used to determine vehicle prohibitions in certain areas and route allocation for public transport following single roads with specific frequency. The direction of flows was elaborated from gauging performed at all intersections in the study area. For streets entering intersections, three possible routes were assigned: continue straight ahead (1), turn left (2), or turn right (3). U-turns were not considered, with data collection conducted simultaneously with gauging work.

Table 4. Vehicle flow within study area

Entry Point	Location	Flow (Veh./h)
1	Jr. Mariscal Llerena	248
2	Av. José Antonio Sucre	266
3	Jr. Los Amautas	34
4	Jr. Luis Carranza	97
5	Psj. Arca Parro	27
6	Av. Nery G. Zarate	197
7	Jr. Hidalgo	111
8	Av. Agustín Gamarra	341

Note: Average gauging was used despite peak hour flow focus, as flow was not homogeneous. Stochastic behavior was assigned in Vissim to behave heterogeneously as in reality.

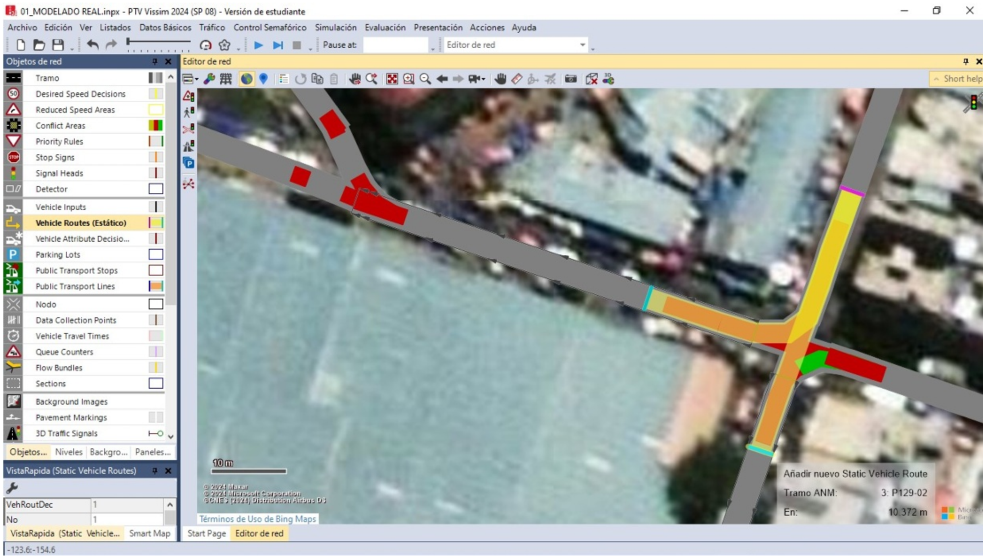

Figure 8. Assignment of static routes

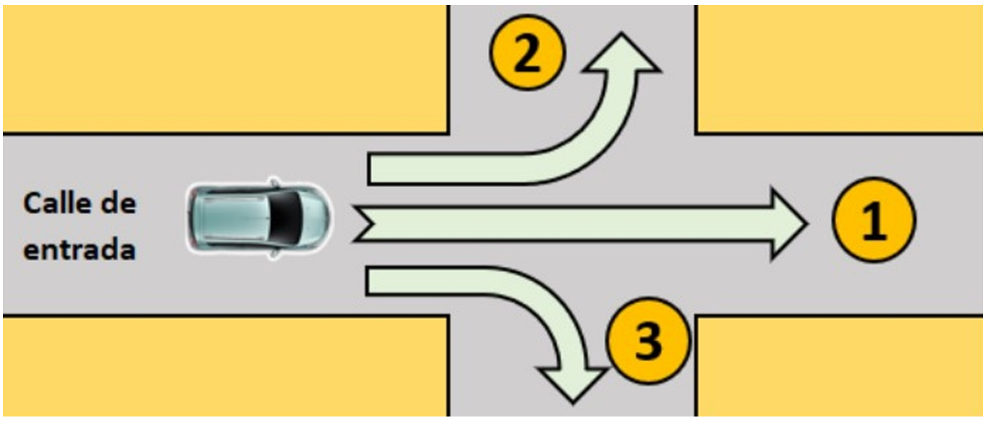

Figure 9. Route assignment

The direction of flows was elaborated from gauging performed at all intersections in the study area. For streets entering intersections, three possible routes were assigned: continue straight ahead (1), turn left (2), or turn right (3). U-turns were not considered, with data collection conducted simultaneously with gauging work.

3.5.4 Priority of passage and intersection control

After establishing income and flow distribution, priority of passage was determined through observation during vehicular capacity analysis. Within the study area, no priority passage exists—it is indeterminate, leading to vehicles attempting to cross without yielding to other approaching vehicles, consequently exposing intersections to vehicular disorder and congestion formation on incoming roads. Figure 10 illustrates the intercept conflict areas where all intersections were assigned undetermined right-of-way priorities, as complete right-of-way priority introduction is not fully integrated into Ayacucho driver behavior patterns (aggressive driving characteristics).

Figure 10. Intercept conflict area

All intersections were assigned undetermined right-of-way priorities, as complete right-of-way priority introduction is not fully integrated into Ayacucho driver behavior patterns (aggressive driving characteristics).

3.5.5 Vehicle parking modeling

The study area contains one private parking facility on Jirón Hidalgo with 38-vehicle capacity. Streets surrounding Nery García Zarate Market within the study area are not established as public parking zones. The research objective proposes private parking zones or public parking through on-street parking meter systems. As shown in Figure 11, street saturation with parked vehicles, combined with persistent street commerce, necessitated modeling only streets with minimum allowed width of 3.5–4 m. This selection ensured modeling and calibration accuracy as close to reality as possible.

Figure 11. Parked vehicles and street commerce

Street saturation with parked vehicles, combined with persistent street commerce, necessitated modeling only streets with minimum allowed width of 3.5–4 m. This selection ensured modeling and calibration accuracy as close to reality as possible.

3.5.6 Mesoscopic behavior and parameter calibration

Calibration incorporated Ayacucho traffic characteristics, representing disorderly operation caused by drivers leading to vehicular chaos. These aspects are integrated within PTV Vissim to better represent conflicts within the study area. Mesoscopic parameters influencing vehicle behavior include reaction times, stopping separation, and speeds. Free-flow speed represents the speed vehicles desire when facing no delay constraints, typically exceeding average travel speed. Field measurements of vehicle speeds were conducted at various network points, ensuring vehicle paths were free of delay constraints during speed recording, with results presented in Table 5. Note that linear motorcycles and mototaxis demonstrate greater maneuverability within the network. Trucks maintain higher speeds due to space availability, expecting smaller vehicles to advance by using available lanes and completing segments in shorter time. Cars and buses move at lower speeds due to passenger pickup requirements during displacement.

Table 5. Vehicle speeds within study area

Vehicle Type	Average Speed (km/h)
Motorcycle	7.98
Mototaxi	13.46
Car	9.21
Bus	5.91
Truck	13.55

Note: Linear motorcycles and mototaxis demonstrate greater maneuverability within the network. Trucks maintain higher speeds due to space availability, expecting smaller vehicles to advance by using available lanes and completing segments in shorter time. Cars and buses move at lower speeds due to passenger pickup requirements during displacement.

Average travel speed was estimated by recording travel time for given roadway lengths. This measurement was developed for each vehicle type introduced in modeling. The research required considering travel speeds of all vehicle types due to representative speeds and numbers within the study area. Average travel speed obtained was 6.30 km/h.

3.6 Model Calibration and Statistical Validation

3.6.1 Calibration methodology and network stability

Model calibration ensured proper PTV Vissim functioning through field-collected information. Meso-simulation calibration consisted of distributing related vehicles in existing nodes with their characteristics (direction, lane numbers, entry and exit), introducing total entry volume in corresponding roads with representative characteristics found in the field. Figure 12 shows the vehicle density evolution in the network during simulation. Network stability time was defined as time required for the network to reach constant vehicle density. Vehicles were introduced into the study area to reach calculated average density, achieved from the fourth minute onwards. Vehicle variation by type was also observed, with density stability from the fourth minute onwards.

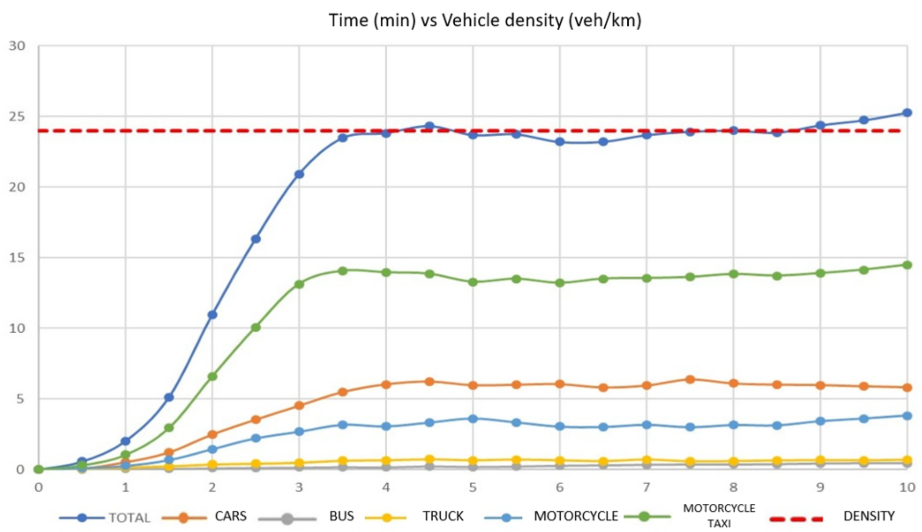

Figure 12. Vehicle density in the network during simulation

Network stability time was defined as time required for the network to reach constant vehicle density. Vehicles were introduced into the study area to reach calculated average density, achieved from the fourth minute onwards. Vehicle variation by type was also observed, with density stability from the fourth minute onwards.

3.6.2 Statistical validation process

Table 6 presents the travel times obtained from 20 simulation runs for model validation. Model calibration employed the null hypothesis model of equality of means using Statkey-Randomization Test program for nonparametric testing with 95% confidence level. Field data average was 15.38 seconds and simulation average was 13.91 seconds, with absolute difference of -1.47 within the range [-2.086, 2.121], guaranteeing model calibration by travel time. Figure 13 illustrates the null hypothesis test for calibration. Statistical validation confirmed at 95% confidence level, accepting null hypothesis ($\mu_1 = \mu_2$) with sufficient statistical evidence affirming model calibration.

Table 6. Travel time for validation

Simulation Order	Travel Time (seconds)
1	14.24
2	13.44
3	14.46
4	13.25
5	13.89
6	13.72
7	13.82
8	13.74
9	14.06
10	14.26
11	13.32
12	13.37
13	14.19
14	14.20
15	13.93
16	14.27
17	13.52
18	14.36
19	13.33
20	13.97
Average	13.87

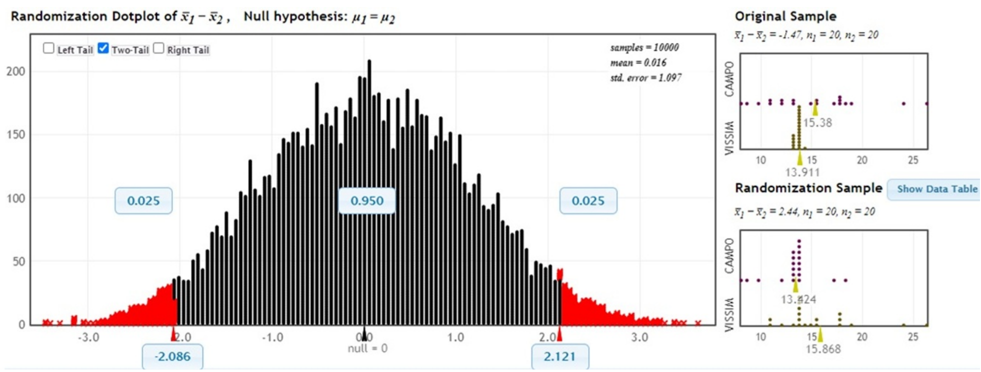

Figure 13. Null hypothesis test calibration

Validation by travel time for each vehicle used data obtained in the field at peak hour, comparing with program-provided data. Field data average was 15.57 seconds and Vissim data was 13.867 seconds, with absolute difference of -1.71 within range [-2.133, 2.135], guaranteeing model validation. Figure 14 illustrates the null hypothesis test for validation, confirming statistical validation at 95% confidence level, accepting null hypothesis ($\mu_1 = \mu_2$) with sufficient statistical evidence affirming model validation.

Statistical analysis confirmed at 95% confidence level, accepting null hypothesis ($\mu_1 = \mu_2$) with sufficient statistical evidence affirming model validation.

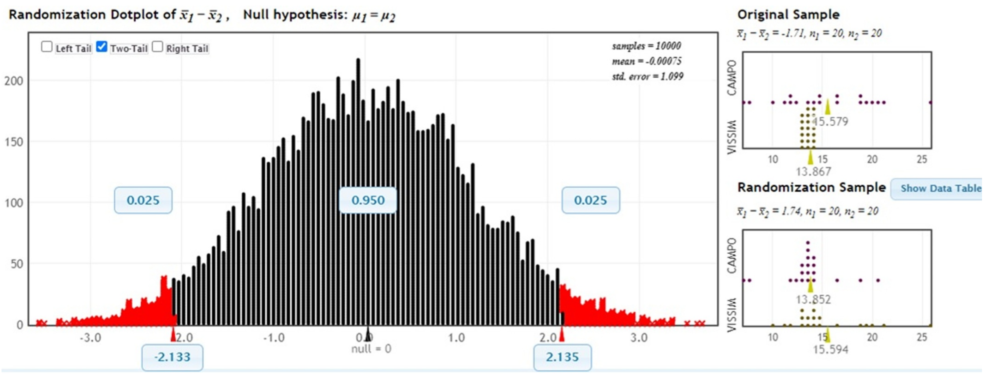

Figure 14. Null hypothesis test validation

3.7 Traffic Management Scenario Development

3.7.1 Intervention strategy design

Traffic regulatory instruments proposed to reduce vehicular traffic within the study area, modeled with PTV Vissim program to observe behavior, include:

1. Road conditioning (Mariscal Llerena block 02 and Psj. 128);
2. Heavy vehicle access restriction during peak hours;
3. Direction changes at Entry 02 and Entry 05.

3.7.2 Traffic light implementation strategy

Figure 15 shows the proposed locations where traffic signal implementation was proposed as alternative solution to regulate vehicular entry at interceptions. Using PTV Vissim modeling, traffic light use was evaluated as favorable at two interceptions: Pasaje 129-Av. Agustín Gamarra and Pasaje 129-Av. Nery García Zarate-Jr. Condorcunca. Cycles were calculated using established methodology.

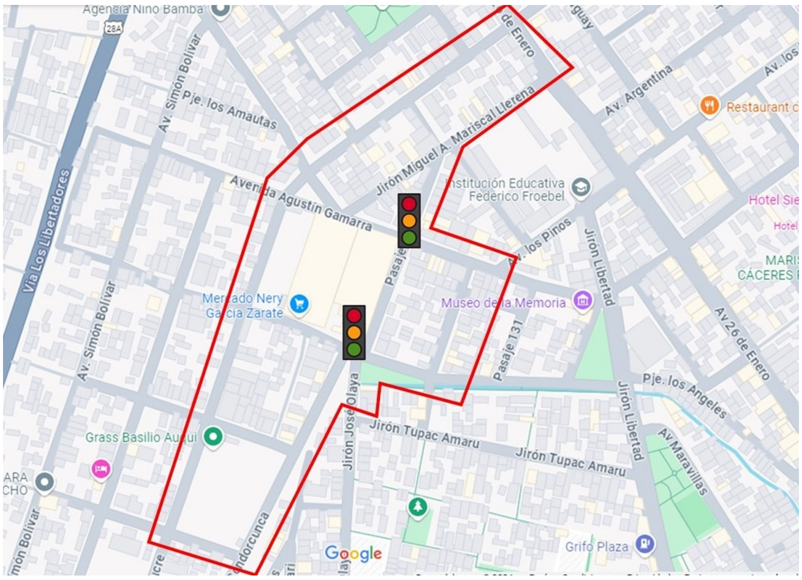

Figure 15. Location of traffic lights

3.7.3 Flow direction modification strategy

Figure 16 illustrates the proposed pathways for flow direction changes that were proposed for streets currently used for vehicular flows in both directions, where vehicle conflicts occur in the same lane. The objective was to change flow directions within study area roads to increase vehicular flow in single directions, using PTV Vissim modeling to evaluate different solutions and benefits in intersection delays around Nery García Zarate market. Direction changes were designed to eliminate vehicular conflicts and optimize traffic flow efficiency through conversion from bidirectional to unidirectional operation on strategic streets as detailed in Table 7.

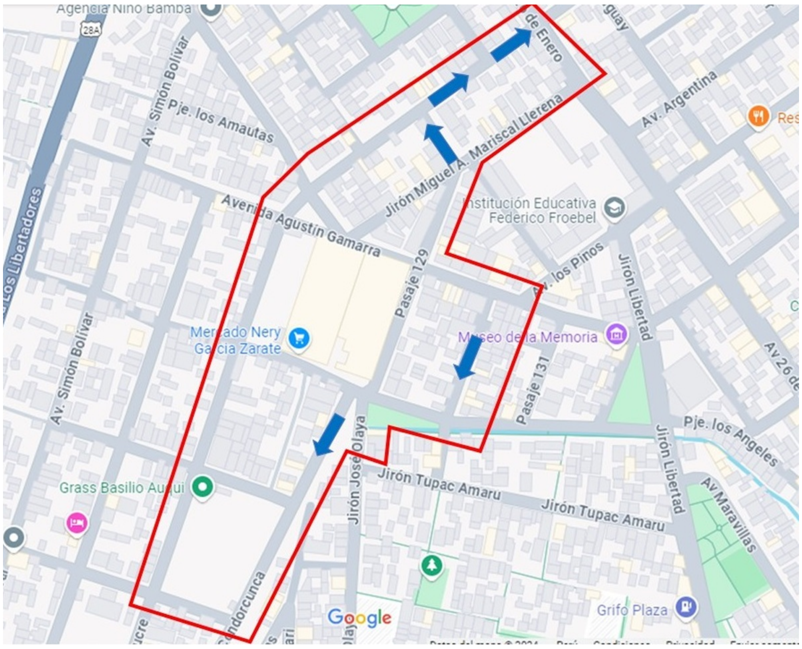

Figure 16. Proposed pathways for a change

Table 7. Roads proposed to close vehicular flow

Simulation Run	Proposed Streets
1	Jr. Condorcunca (Cdra. 1) (S-N)
2	Pasaje 130 (S-N)
3	Pasaje Tarapaca (N-S)
4	Av. José A. de Sucre (Cdra. 1) (E-O)
5	Av. José A. de Sucre (Cdra. 2) (E-O)

Note: Direction changes designed to eliminate vehicular conflicts and optimize traffic flow efficiency through conversion from bidirectional to unidirectional operation on strategic streets.

3.8 Performance Measurement and Economic Analysis Framework

3.8.1 Traffic performance indicators

Model evaluation focused on key traffic performance parameters including travel time, average delays, and average speed measurements. These indicators were selected to assess intervention effectiveness and provide quantitative comparison between current conditions and proposed improvements through behavior evaluation of parameters such as travel time, average delays, and average speed.

3.8.2 Parking meter system analysis

Economic evaluation incorporated parking meter system viability analysis as optional measure. Maximum road capacity calculation was determined through cordon gauging, showing vehicle numbers less than maximum road capacity. Parking meter system consideration focused on roads where roadway width would not be subsequently damaged and vehicular traffic is critical, discounting 6m at each corner as recommended by MTC (2018).

3.8.3 Economic analysis methodology

Cost-benefit analysis was conducted to assess financial sustainability of proposed traffic management interventions, including implementation costs, operational expenses, and revenue generation potential for municipal decision-making processes.

The methodology establishes a comprehensive framework for systematic evaluation of traffic management strategies in commercial districts of developing cities, providing evidence-based analysis for municipal traffic management planning and implementation.

4 Results

4.1 Current Traffic Conditions and Baseline Assessment

4.1.1 Parking supply-demand analysis

Field data collection during peak hours (11:30–12:30 AM) revealed critical infrastructure deficiencies in the study area around Nery García Zarate Market. Table 8 summarizes the parking supply versus demand analysis, showing that street parking demand reaches 324 equivalent vehicles during peak hours, vehicles in rigid zones total 318 equivalent vehicles, formal parking supply provides only 38 vehicles on Jr. Hidalgo, vehicles in formal parking total 6 equivalent vehicles, and the supply deficit reaches 286 equivalent vehicles (88.3% of demand). Data were collected through direct field observation during peak hours (11:30–12:30 AM). The 286-vehicle deficit represents vehicles circulating searching for parking spaces.

Table 8. Parking supply vs demand analysis

Parameter	Current Value	Significance
Street parking demand	324 equiv. vehicles	Peak hour
Vehicles in rigid zones	318 equiv.vehicles	Unregulated
Formal parking supply	38 vehicles	Jr.Hidalgo
Vehicles in formal parking	6 equiv. vehicles	Low utilization
Supply deficit	286 equiv. vehicles	88.3% of demand

Note: Data collected through direct field observation during peak hours (11:30–12:30 AM). The 286-vehicle deficit represents vehicles circulating searching for parking spaces.

4.1.2 Road capacity utilization assessment

Maximum road capacity analysis demonstrated that congestion is not caused by volume-capacity constraints but by parking-seeking behavior. Tables 9 and 10 present the road capacity analysis results for primary and secondary streets. Maximum capacity was calculated using HCM 2016 standards. Average utilization of 18.8% confirms congestion is caused by parking-seeking behavior, not road capacity constraints.

Table 9. Road capacity analysis—primary streets

Street	Max Capacity (veh/h)	Observed Volume (veh/h)
Jr. Mariscal Llerena	751	218
Pasaje 129 (Cdra 2)	770	133
Jr. Condorcunca (Cdra 1)	897	144
Jr. Condorcunca (Cdra 2)	897	95

Table 10. Road capacity analysis—secondary streets

Street	Max Capacity (veh/h)	Observed Volume (veh/h)
Av. José A. Sucre (Cdra. 1)	1,109	380
Av. José A. Sucre (Cdra. 2)	1,168	296
Av. Agustín Gamarra (Cdra. 1)	760	199
Network Average	898.63	169.0

Note: Maximum capacity calculated using HCM 2016 standards. Average utilization of 18.8% confirms congestion is caused by parking-seeking behavior, not road capacity constraints.

4.2 Model Calibration and Statistical Validation

4.2.1 PTV Vissim Model Accuracy Assessment

The microsimulation model achieved acceptable accuracy standards through rigorous validation procedures using field data collected during peak congestion periods. Table 11 presents the model validation results, showing average travel time from field data of 15.57 $\pm$ 3.42 seconds compared to simulation data of 13.87 $\pm$ 2.89 seconds, with a travel time difference of -1.70 seconds. Travel time validation was based on 20 field measurements during peak hours. Wilcoxon test was selected due to non-normal distribution (Shapiro-Wilk $p < 0.05$). The model meets international validation standards with Wilcoxon $p = 0.047$, indicating acceptable accuracy.

Table 11. Model validation results

Validation Parameter	Field Data	Simulation Data
Average travel time (s)	15.57 ± 3.42	13.87 ± 2.89
Travel time difference	-	-1.70 seconds
Statistical test	Wilcoxon $p = 0.047$	Acceptable

Note: Travel time validation based on 20 field measurements during peak hours. Wilcoxon test selected due to non-normal distribution (Shapiro-Wilk $p < 0.05$). Model meets international validation standards.

4.3 Traffic Intervention Performance Analysis

4.3.1 Comprehensive solution performance (recommended approach)

The integrated approach combining flow direction optimization with parking management interventions demonstrated optimal network-wide performance improvements.

Network performance evaluation categorized intersections by hierarchical importance to assess differential intervention impacts. Tables 12 and 13 present the comparative delay analysis for primary and secondary intersections, respectively, showing current conditions versus integrated solution performance. Primary intersections are located along main arterial corridors (Av. J.A. Sucre), while secondary intersections are concentrated around the Nery García Zarate market area. The integrated solution achieved significant delay reductions across both intersection categories, demonstrating an overall network improvement of 31.0%.

Table 12. Network performance—primary intersections

Intersection	Current Delay (s)	Integrated Solution (s)
Av. J.A. Sucre-Jr. Los Amautas	2.46	1.07
Av. J.A. Sucre-Psj. Tarapaca	14.44	3.18
Av. J.A. Sucre-Jr. Luis Carranza	9.61	4.64
Av. J.A. Sucre-Psj. Arca Parro	21.73	17.25

Table 13. Network performance—secondary intersections

Intersection	Current Delay (s)	Integrated Solution (s)
Psj. 129-Av. Agustín Gamarra	16.03	1.82
Psj. 129-Av. Nery García Zarate	19.78	10.67
Av. N. García Zarate-Jr. Condorcunca	13.63	8.24
Network Average	160.87	110.94

Note: Intersection delays measured through field observation using stopwatch methodology. Integrated solution combines flow direction changes with parking management. Overall network improvement: 31.0% (Wilcoxon $p = 0.047$).

4.3.2 Individual intervention effectiveness analysis

- Traffic signal implementation analysis (not recommended)

Statistical analysis of traffic signal installation revealed significant deterioration in network performance across all measured parameters. Table 14 presents the traffic signal implementation results, showing signal timing calculated using Webster's method. Results show a 54.9% increase in delays (Wilcoxon $p = 0.776 > 0.05$), indicating traffic signals are contraindicated for this network configuration.

Table 14. Traficall signal implementarion results

Intersection	Current Delay (s)	With Signals (s)
Psj. 129-Av. Agustín Gamarra	16.03	23.06
Psj. 129-Av. Nery García Zarate	19.78	26.7
Network Total	160.87	249.15

Note: Signal timing calculated using Webster's method. Results show 54.9% increase in delays (Wilcoxon $p = 0.776 > 0.05$), indicating traffic signals are contraindicated for this network configuration.

- Flow direction optimization analysis (Most effective individual strategy)

Unidirectional flow implementation on five strategic streets achieved optimal individual intervention performance with significant statistical validation. Table 15 details the flow direction changes, showing modifications from bidirectional to unidirectional flow on Jr. Condorcunca (Cdra. 1) to S-N only, Pasaje 130 to S-N only, Pasaje Tarapaca to N-S only, and Av. José A. Sucre (Cdra. 1-2) to E-O only. Flow direction changes eliminate conflict points and optimize capacity utilization, achieving the highest individual performance improvement (33.2%) with statistical significance (Wilcoxon $p = 0.011 < 0.05$), requiring only signage and lane marking modifications.

Table 15. Flow direction changes—performance results

Modified Street	Current Direction	Proposed Direction
Jr. Condorcunca (Cdra. 1)	Bidirectional	S-N only
Pasaje 130	Bidirectional	S-N only
Pasaje Tarapaca	Bidirectional	N-S only
Av. José A. Sucre (Cdra. 1–2)	Bidirectional	E-O only

Note: Flow direction changes eliminate conflict points and optimize capacity utilization. Achieved highest individual performance improvement (33.2%) with statistical significance, requiring only signage and lane marking modifications.

Performance Results: 33.2% delay reduction (160.87 $\rightarrow$ 107.47s), Wilcoxon $p = 0.011$ <0.05 (significant).

4.4 Economic Impact and Implementation Analysis

4.4.1 Parking meter system financial viability

The parking meter system demonstrates strong economic viability with rapid cost recovery and sustainable revenue generation. Tables 16 and 17 present the parking meter economic analysis, showing that 205 units are required based on street capacity analysis, implementation cost totals S/180,000 at S/878 per unit, and monthly gross revenue reaches S/59,040 under an 80% utilization scenario. Economic analysis is based on 2023 Ayacucho costs and S/0.50 per 30-minute rate. Statistical validation (T-test $p = 0.001$) confirms highly significant benefits for free traffic transit, with operating costs of S/21,600 monthly (S/259,200 annually), net revenue of S/37,440 monthly (S/449,280 annually), and a payback period of 4.8 months.

Table 16. Parking meter economic analysis

Economic Parameter	Value	Calculation Basis
Total meters required	205 units	Street capacity analysis
Implementation cost	S/180,000	S/878 per unit
Monthly gross revenue	S/59,040	80% utilization scenario

Table 17. Parking meter financial results

Parameter	Monthly Value	Annual Value
Operating costs	S/21,600	S/259,200
Net revenue	S/37,440	S/449,280
Payback period	4.8 months	-

Note: Economic analysis based on 2023 Ayacucho costs and S/0.50 per 30-minute rate. Statistical validation (T-test $p = 0.001$) confirms highly significant benefits for free traffic transit.

4.4.2 Private parking zone development analysis

Strategic parking zone development addresses the identified supply deficit through optimally located facilities with adequate capacity and accessibility. Table 18 details the private parking zone infrastructure planning, showing Zone 01 on Jr. Hidalgo expansion with 85 vehicle capacity, Zone 02 in the market northeast area with 85 vehicle capacity, Zone 03 on Pasaje 129 triangle with 44 vehicle capacity, totaling 214 vehicles across all zones. Proposed zones address 74.8% of the 286-vehicle parking deficit. Total development cost: S/320,000 including land preparation, pavement, lighting, and access control infrastructure.

4.5 Statistical Hypothesis Testing and Validation

4.5.1 Formal research hypothesis evaluation

All research hypotheses were rigorously tested using appropriate statistical methodologies with predetermined significance levels ($\alpha = 0.05$). Table 19 summarizes the comprehensive hypothesis testing results, showing that H_1

(Regulatory instruments improve traffic) achieved significant improvement with Wilcoxon p = 0.047, H_2 (Private parking zones beneficial) showed beneficial impact with Wilcoxon p = 0.102, H_3 (Combined approach effective) demonstrated marginal significance with Wilcoxon p = 0.069, and H_4 (Parking meters benefit traffic) showed highly significant results with t-test p = 0.001. Statistical tests were conducted using IBM SPSS Statistics at α = 0.05. Wilcoxon signed-rank tests were used for non-parametric paired comparisons; t-test was used for normally distributed parking meter data.

Table 18. Private parking zone infrastructure planning

Parameter	Location	Capacity
Zone 01	Jr.Hidalgo expansion	85 veh
Zone 02	Market northeast area	85 veh
Zone 03	Pasaje 129 triangle	44 veh
Total	All zones	214 veh

Note: Proposed zones address 74.8% of the 286-vehicle parking deficit. Total development cost: S/320,000 including land preparation, pavement, lighting, and access control infrastructure.

Table 19. Comprehensive hypothesis testing results

Hypothesis	Test/p-value	Conclusion
H_1 : Regulatory instruments improve traffic	Wilcoxon p = 0.047	Significant improvement
H_2 : Private parking zones beneficial	Wilcoxon p = 0.102	Beneficial impact
H_3 : Combined approach effective	Wilcoxon p = 0.069	Marginal significance
H_4 : Parking meters benefit traffic	t-test p = 0.001	Highly significant

Note: Statistical tests conducted using IBM SPSS Statistics at α = 0.05. Wilcoxon signed-rank tests used for non-parametric paired comparisons; ttest used for normally distributed parking meter data.

4.6 Implementation Feasibility and Study Constraints

4.6.1 Municipal implementation requirements

Infrastructure Investment and Resource Allocation:

- Flow direction modifications: S/45,000 (signage, lane markings, traffic barriers);
- Parking meter system installation: S/180,000 (205 meters with complete setup);
- Private parking zone development: S/320,000 (land preparation and infrastructure);
- Total municipal infrastructure investment: S/545,000;

Operational Requirements:

- Parking meter enforcement personnel: 8 dedicated officers (S/2,700 monthly salary each);
- Monthly operational expenses: S/21,600 (personnel costs plus equipment maintenance);
- Projected annual net revenue: S/449,280 from parking meter operations;
- Implementation timeline: 6-month phased deployment for optimal traffic transition management.

4.7 Study Limitations and Research Constraints

Methodological and Data Collection Limitations:

- Temporal scope restriction: Analysis conducted exclusively during peak hour period (11:30–12:30 AM) may not adequately represent daily traffic variation patterns;
- Seasonal data collection constraint: 30-day observation period during single season insufficient for comprehensive annual traffic pattern analysis;
- Behavioral modeling simplifications: Exclusion of U-turn maneuvers frequently observed at Pasaje 129-Jr. Condorcunca intersection may underestimate intersection complexity by approximately 8–12%;
- Local driving pattern approximation: Ayacucho driving culture characteristics may introduce ± 10–15% variability in delay predictions compared to model estimations.

Generalizability and Application Boundaries:

- Geographic and altitude specificity: Results specifically applicable to Ayacucho urban market context at 2,761 m elevation;
- Economic context dependency: Cost-benefit analyses based on 2023 local wage structures (minimum wage S/930/month) and municipal budget constraints;

• Regulatory framework assumptions: Analysis assumes consistent municipal enforcement capabilities and legal authority for traffic regulation implementation;

• Infrastructure assumption constraints: Implementation feasibility based on current road conditions and physical space availability.

5 Discussion

5.1 Key Findings Interpretation

The 31.0% delay reduction achieved through integrated traffic management confirms that parking-seeking behavior, not road capacity constraints, is the primary congestion driver in market areas. The low road utilization (18.8%) supports demand management over infrastructure expansion as the optimal intervention strategy.

The contraindication of traffic signals (54.9% performance degradation, $p = 0.776$) provides critical insight for traffic engineering in low-volume, mixed-traffic environments. This finding suggests that conventional traffic control assumptions may not apply in developing urban contexts where natural traffic flow patterns are more efficient than rigid signal control.

5.2 Methodological Contributions

The successful application of PTV Vissim with non-parametric validation methods (Wilcoxon tests) demonstrates appropriate microsimulation techniques for informal traffic patterns. The integration of parking demand analysis with traffic flow modeling provides a comprehensive framework addressing both capacity and demand management simultaneously.

The statistical validation approach (formal hypothesis testing at $\alpha = 0.05$) enables evidence-based prioritization of interventions, supporting municipal resource allocation decisions with quantitative justification.

5.3 Policy and Implementation Implications

5.3.1 Municipal decision framework

Statistical validation provides clear intervention prioritization:

• Flow direction changes ($p = 0.011$): Highest effectiveness, lowest cost;

• Parking meters ($p = 0.001$): Revenue-generating with strong statistical support;

• Traffic signals ($p = 0.776$): Resources better allocated elsewhere.

5.3.2 Economic sustainability model

The 4.8-month payback period and S/449,280 annual net revenue demonstrate financial viability for similar developing urban contexts. This economic model addresses the common challenge of long-term funding for traffic management operations.

5.4 Study Limitations

The temporal scope limitation (peak hour only) and geographic specificity (Ayacucho, 2,761m elevation) constrain direct transferability. Modeling simplifications (U-turn exclusion, simplified driving behavior) introduce $\pm$ 8–15% uncertainty in delay predictions. These limitations reflect inherent trade-offs between analytical feasibility and real-world complexity.

5.5 Future Research Priorities

Immediate Research Needs:

1. Temporal extension: Full daily cycle and seasonal validation studies;
2. Geographic scalability: Multi-city comparative analysis across different elevations and economic contexts;
3. Long-term sustainability: 12–24 month post-implementation monitoring.

Methodological Development:

4. Pedestrian-vendor integration: Quantification methods for informal commerce impacts;
5. Simplified modeling tools: Resource-efficient approaches for municipal planning applications.

Policy Research:

6. Enforcement optimization: Sustainable institutional frameworks for traffic management;
7. Technology integration: Low-cost sensor networks and mobile payment systems for developing cities.

The study establishes a replicable framework for evidence-based traffic management in developing urban market contexts while identifying critical areas for methodological advancement and broader application.

6 Conclusions

This study demonstrates that calibrated mesoscopic simulation effectively optimizes traffic performance in commercial districts of developing cities. The comprehensive analysis around Nery García Zarate Market provides evidence-based insights for municipal traffic management while establishing a replicable methodological framework.

The research confirms that parking-seeking behavior, rather than road capacity constraints, drives traffic congestion in market areas. Field observations revealed a critical deficit of 286 equivalent vehicles during peak hours, while road utilization averaged only 18.8%. These finding challenges conventional infrastructure expansion approaches, demonstrating that effective solutions must address behavioral patterns rather than physical capacity.

Statistical validation provides definitive guidance for resource allocation. Traffic regulatory instruments achieved significant delay reduction from 10.72 to 7.40 seconds (31.0% improvement, $p = 0.047$). Flow direction optimization proved most effective individually, achieving 33.2% improvement ($p = 0.011$) with minimal investment. Conversely, traffic signals increased delays by 54.9% ($p = 0.776$), proving counterproductive in low-volume, mixed-traffic environments where natural flow patterns exceed rigid control effectiveness.

Economic analysis demonstrates strong viability with parking meters achieving 4.8-month payback and S/449,280 annual revenue. The 214 additional parking spaces across three strategic zones address 74.8% of the deficit while enabling sustainable public-private partnerships. This model addresses the fundamental funding challenge for traffic management in developing cities.

Methodological contributions include successful PTV Vissim application in developing urban contexts and integration of parking demand with traffic flow modeling. Non-parametric validation methods address informal traffic pattern characteristics, while formal hypothesis testing enables evidence-based municipal decisions.

The study acknowledges important limitations: temporal restriction to peak hours, geographic specificity to Ayacucho's context (2,761m elevation), and modeling simplifications introducing $\pm$ 8–15% uncertainty. These constraints reflect trade-offs between analytical feasibility and real-world complexity typical in municipal traffic studies.

Future research priorities include temporal extension to daily cycles and seasonal variations, multi-city comparative analysis, and long-term sustainability assessment. Methodological development opportunities encompass pedestrian-vendor interaction modeling, simplified tools for resource-constrained municipalities, and integration of emerging monitoring technologies.

The findings contribute to limited literature on traffic management in developing urban commercial districts while establishing an evidence-based municipal decision framework. The statistical validation approach enables intervention prioritization based on quantitative effectiveness rather than conventional assumptions, supporting efficient allocation of scarce resources. This research demonstrates that context-specific, statistically validated traffic engineering approaches can achieve substantial performance improvements in developing urban environments, providing a foundation for sustainable mobility solutions in rapidly growing cities.

Author Contributions

Conceptualization: H.L.A., L.E.B.E., and R.G.B.A.; Methodology: H.L.A., L.E.B.E., and R.G.A.B.; Software (PTV Vissim): H.L.A., A.S.I.H., R.G.B.A., and D.O.T.-H.; Validation: H.L.A., L.E.B.E., R.G.B.A., and D.O.T.-H.; Formal analysis: H.L.A., L.E.B.E., R.G.B.A., and A.T.G.; Investigation: H.L.A., A.S.I.H., R.G.A.B., A.T.G., E.C.G.S., S.W.R.F., and D.O.T.-H.; Resources: H.L.A. and D.O.T.-H.; Data curation: H.L.A., A.S.I.H., and R.G.B.A.; Writing—original draft: H.L.A., L.E.B.E., and R.G.B.A.; Writing—review and editing: H.L.A., L.E.B.E., R.G.B.A., R.G.A.B., A.T.G., and D.O.T.-H.; Visualization: H.L.A., A.S.I.H., E.G.S., and D.O.T.-H.; Supervision: L.E.B.E. and D.O.T.; Project administration: H.L.A. and L.E.B.E.; Technical translation: D.O.T.-H. All authors have read and approved the published version of the manuscript.

Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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