Evaluating the Impact of Traffic Control System Failures on Intersection Level of Service Using Microsimulation

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Abstract. Traffic control systems play a critical role in ensuring an adequate level of safety at intersections for transport infrastructure users. At the same time, key performance parameters such as delay, travel time, and queue length are monitored from the design and implementation stages of these systems. However, real-world operation may lead to system malfunctions, generating negative effects on users that can be quantified through variations in the aforementioned performance parameters. The impact of such events can be assessed through analytical scenarios implemented within microsimulation models. In this study, the authors developed a simulation environment for a heavily trafficked intersection in Bucharest and generated a series of risk scenarios. The results obtained here support the development of a maintenance strategy for traffic control system components that accounts for the negative impacts induced by their failures.

Keywords: Traffic control systems · Microsimulation models · Intersection performance; Level of Service (LOS)

1 Introduction

Within urban transportation networks, signalized intersections are critical operational nodes, and traffic control systems ensure both safe efficient traffic and operation. According to the latest editions of the Highway Capacity Manual [1], the performance of these systems is typically evaluated using quantitative indicators (delays, queue length, and volume-to-capacity ratio), which form the basis for determining the Level of Service (LOS).

Recent research in the field of traffic engineering has increasingly emphasized performance monitoring and the evaluation of signalized intersections based on historical or real-time data. Traffic control systems rely on multiple hardware and software components, including detectors, controllers, communication units, and power supply systems.

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Failures affecting these components can alter the actual duration of the green light, disrupt the phase sequence, or cause the traffic signal to operate inefficiently.

Over the past decade, the concept of road infrastructure resilience has received increasing attention in transportation literature. Recent studies emphasize robustness, fault tolerance, and system recovery under degraded operating conditions [2]. Many of these contributions adopt a network-level or conceptual perspective, while detailed quantification at the intersection level of efficiency loss in the event of traffic control system failures remains limited.

For evaluating intersection performance under complex traffic conditions, microscopic traffic simulation has become a fundamental tool. Simulation tools, such as PTV Vissim, enable detailed representation of vehicle following behavior, lane-changing dynamics, control logic, and demand variability [3]. More recent applications of microsimulation have demonstrated its suitability for assessing the operational impact of non-standard scenarios, including demand surges, incident conditions, and traffic signal synchronization failures [4]. However, structured evaluations that integrate explicit traffic control system failure scenarios with HCM-based service level assessment remain insufficiently explored.

In this context, the present study examines the impact of traffic control system failures on intersection service levels using microsimulation techniques. A detailed simulation model was developed for a high-traffic urban intersection in Bucharest, replicating observed demand patterns and signal configurations. Several risk scenarios representing component-level failures were implemented in the simulation environment. By comparing operational indicators under normal and degraded conditions, the study quantifies the extent to which traffic control system failures affect intersection performance and supports the development of maintenance strategies based on measurable operational impacts.

Although safety is one of the fundamental objectives of traffic control systems, this study focuses on operational performance—delay, queue length, and level of service—under normal conditions and degraded operating conditions. The safety implications are beyond the scope of this paper but underscore the importance of system reliability.

The remainder of the paper is organized as follows. Section 2 reviews relevant studies on traffic control systems and microsimulation. Section 3 defines the methodology and principles for conducting the case study. Section 4 presents the simulation results for all three operational scenarios. Section 5 discusses the results, concludes the paper and presents both the conclusions and the implications.

2 Literature Review

Traffic Control Systems (TCS) constitute a strategic operational infrastructure in urban transportation networks by integrating signal controllers, detection devices, communication modules, and power supply components into a coordinated decision-making framework. Their primary objective is to ensure the safe and efficient allocation of right-of-way.

In the context of TCS, degraded performance can result from hardware failures, detection failures, communication instability, or power outages. Analyses of infrastructure interdependencies highlight that component-level failures can generate cascading

operational impacts beyond immediate hardware failures [5]. The traffic detector failures represent one of the most common causes of traffic control system degradation. Empirical research on detection accuracy and anomaly identification demonstrates that compromised detector inputs significantly influence operational efficiency [6].

Traffic flow modeling has evolved from continuous macroscopic approaches to detailed microscopic behavioral representations. The kinematic wave theory introduced by Lighthill and Whitham (1955) [7] and Richards (1956) [8] established the theoretical foundations for describing the propagation of congestion and the dynamics of shockwaves in road networks. Microscopic modeling approaches, including the vehicle tracking model proposed by Gipps (1981) [9], allow for the explicit simulation of individual vehicle dynamics under stop-and-go conditions. Comprehensive reviews of traffic flow modeling frameworks are provided by Treiber and Kesting (2013) [10], who emphasize the importance of microscopic approaches in capturing nonlinear interactions, stochastic arrival models, and the behavior of queue clearance. Although traditional approaches to traffic modeling remain relevant, recent studies show a noticeable evolution. These have focused on integrating intelligent data collection systems and digital tools into traffic analysis frameworks. Such approaches help improve data accuracy and enable a more detailed and realistic modeling of traffic behavior [11, 12].

Numerous studies validate microscopic models for evaluating traffic signal performance and control strategies, including the analysis of delays and queue lengths at signalized intersections [13, 14]. Furthermore, the integration of advanced digital technologies such as digital twins enables dynamic assessments of the performance and efficiency of traffic control infrastructure [15, 16]. Simulation-based analyses have been successfully applied in many studies to assess the impact of infrastructure changes and sustainable mobility solutions, such as Park-and-Ride systems and traffic allocation algorithms [17, 18]

Despite advances in simulation-based analysis, most studies focus on optimization, capacity improvement, or demand variability, rather than on the explicit modeling of failures in traffic control system components. The combined integration of (i) TCS reliability degradation, (ii) LOS assessment, and (iii) microscopic scenario modeling remains underdeveloped.

The literature review initially involved querying the Google Scholar database using Harzing's Publish or Perish (PoP) software, version 8. Studies written in English and accessible to the general public were selected, with no time restrictions. In order to capture the main research directions related to the topic, the search strategy employed a combination of relevant keywords, including "traffic control systems", "microsimulation", "intersection performance", "Level of Service (LOS)", and "traffic flow". The bibliometric trend illustrated in Fig. 1 confirms a substantial increase in research output related to traffic control systems [19, 20], intersection performance [21], and simulation methodologies [22–24] over the past decades.

The more extensive applicability of traffic analysis based on data can also be demonstrated through intelligent traffic monitoring applications in the logistics sector and in port access areas [25].

The accelerated growth after 2015 reflects advances in the fields of intelligent transportation systems, data analysis, and computational modeling. However, the lack of an

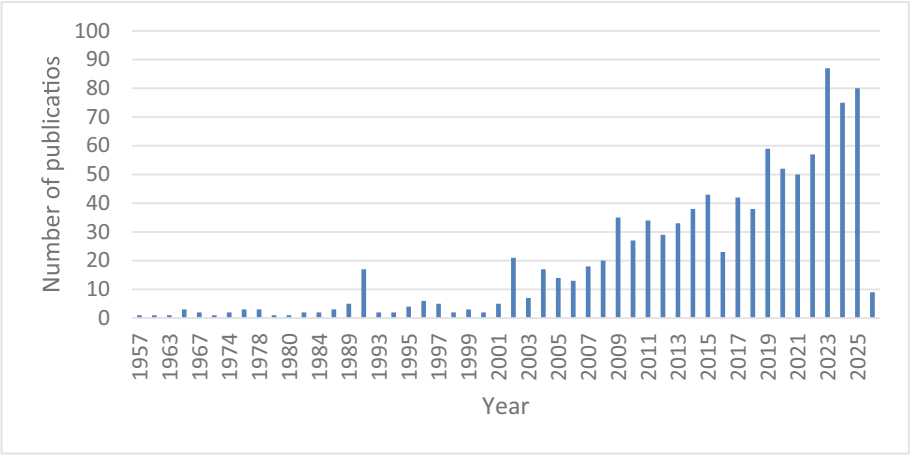

Fig. 1. Annual distribution of scientific publications related to traffic control systems, intersection performance, and microsimulation (1957–2025)

integrated framework that translates traffic control system failures into measurable LOS degradation at the component level remains insufficiently explored.

3 Methodology and Case Study

The experimental design of the study is focused on assessing the impact of the traffic control system on the operational performance of an urban intersection equipped with traffic lights, using a microsimulation-based approach. To this end, analysis scenarios were defined by modifying the parameters governing traffic control and vehicle travel behavior, under conditions of constant traffic demand.

Three operational configurations are considered: (i) standard operation of the traffic signal system, (ii) the emergency mode characterized by flashing yellow lights, which involves the elimination of traffic signal control and the occurrence of conflicting interactions between traffic flows, and (iii) traffic conditions specific to the cold season, implemented by reducing speeds and adjusting travel parameters.

The microsimulation model is configured by defining a detailed set of input parameters specific to the PTV Vissim environment, which describe both traffic demand and vehicle behavior. Traffic demand is entered in the form of input flow volumes at each access point (veh/h), distributed across travel directions (left, straight, right).

Vehicle behavior is modeled using the Wiedemann 99 algorithm by adjusting specific parameters such as CC0 (stopping distance), CC1 (headway), CC2 (headway variation), as well as dynamic acceleration and deceleration parameters. These parameters have a direct influence on the formation and dissipation of queues, evacuation capacity, and traffic flow stability.

Traffic signal timing (green, yellow, and red), cycle duration, and the way signal groups are structured are all operational parameters of the traffic control system. The saturation flow and the effective capacity of the intersection are determined by these

parameters. The values that were used helped calibrate the model against empirical data and represent actual operating conditions.

The Level of Service (LOS) is calculated using the average vehicle delay evaluating the intersection's operational performance. The Highway Capacity Manu-al (HCM) established the criteria for classification (Table 1). Delay values were obtained from the simulation, and LOS served as a benchmark metric for comparing the scenarios examined [1].

Table 1. LOS criteria for signalized intersection (source: [1])

LOS	A	B	C	D	E	F
Control Delay per vehicle (s/veh)	≤10	>10–20	>20–35	>35–55	>55–80	>80

The case study analyzes the intersection of Iuliu Maniu Blvd., Virtuții Road, and Lujerului Street, located in Sector 6 of Bucharest (Fig. 2). It is a signalized intersection classified as a complex urban intersection, characterized by the intersection of a Category I main artery with secondary distribution roads. Iuliu Maniu Boulevard is part of the European E81 network and has multiple lanes in each direction, serving as a major east-west penetration artery. Virtuții Street and Lujerului Street are Category II arteries that allow traffic to flow from north to south and connect with urban networks.

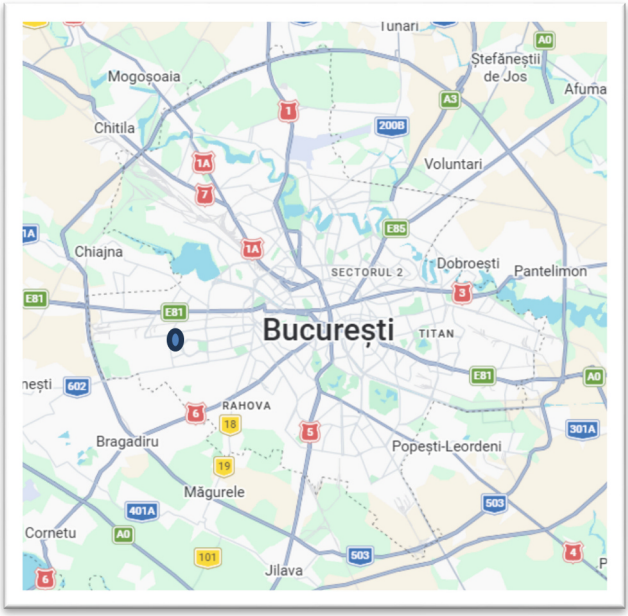

Fig. 2. Location of the analyzed intersection in Bucharest



Fig. 3. Signal group configuration and induction loop detector placement (source: authors).

From a geometric standpoint, the intersection has a complex configuration, with multiple lanes on each approach and dedicated lanes for the main travel modes: left turn, straight-through, and right turn. The analysis is limited to traffic at the signalized intersection, excluding the flows associated with the Lujerului overpass, which are not considered in the simulation model. The east–west direction, corresponding to Iuliu Maniu Blvd, is the dominant direction in terms of traffic volume, leading to high demand on the intersection's capacity. To analyze traffic, directional counts were conducted at the intersection under study using inductive loop detectors placed at the entry and exit points of each access road (Fig. 3). The detection system enabled continuous recording of traffic flows for each travel route.

Traffic data were collected over a period of one week, in February, with 24-h daily coverage. For the subsequent analysis, February 9 was selected as the reference day, being considered representative of typical urban traffic conditions. From the daily recording interval, the time period 07:00–08:00 was chosen, corresponding to the morning peak hour, characterized by high traffic flow values and an increased level of intersection load. The data thus obtained formed the basis for defining the traffic demand in the microsimulation model and for its calibration in relation to real operating conditions. Traffic flows were defined for each approach of the intersection and for each movement relationship, namely left turn, through movement, and right turn, based on the data collected from the field.

The directional distribution (Table 2) highlights the predominance of movements along the east–west direction, corresponding to Iuliu Maniu Boulevard, where the highest traffic volumes are recorded. The north–south direction plays an important role in the

redistribution of flows at the local level, although the volumes are lower. Traffic control at the intersection is managed by a traffic signal system organized into six signal groups, corresponding to compatible traffic flows. The signal plan includes defined green, yellow, and red-light durations for each phase, as well as a cycle time adapted to traffic demand. The main west–east and east–west directions, corresponding to Iuliu Maniu Blvd., have longer green times due to the high traffic volumes on these routes, while the secondary directions are served by shorter green intervals.

Table 2. The simulation input data

Access	Direction	Turn	Direction ID	Percentage [%]	Volume [veh/h]	Total [veh/h]
Blvd. Iuliu Maniu (East)	Straight	→ Blvd. Iuliu Maniu (West)	D01	85%	1870	2200
	Right	→ Rd. Virtuții	D02	5%	110	
	Left	→ St. Lujerului	D03	10%	220	
St. Lujerului (South)	Right	→ Blvd. Iuliu Maniu (East)	D04	10%	176	
	Straight	→ Rd. Virtuții	D05	15%	264	1760
	Left	→ Blvd. Iuliu Maniu (West)	D06	75%	1320	
Blvd. Iuliu Maniu (West)	Right	→ St. Lujerului	D07	10%	195	
	Straight	→ Blvd. Iuliu Maniu (East)	D08	70%	1365	1950
	Left	→ Rd. Virtuții	D09	20%	390	
Rd. Virtuții (North)	Right	→ Blvd. Iuliu Maniu (West)	D10	10%	98	
	Straight	→ St. Lujerului	D11	20%	196	980
	Left	→ Blvd. Iuliu Maniu (East)	D12	70%	686	

Three operating scenarios were developed to evaluate the intersection's performance. Each scenario reflects different conditions of the traffic control system and the traffic environment. To compare the results, each scenario used the same traffic flow values. The scenarios allow for a comparison of the effects on performance indicators, particularly delay and level of service (LOS).

- Scenario 1 – Normal Operation: reflects standard intersection operation with the traffic signal system active
- Scenario 2 – Flashing Yellow: describes a degraded operating condition in which the traffic signal system is not active, and traffic flows based on right-of-way rules.
- Scenario 3 – Winter conditions: reflects a situation characterized by reduced vehicle speeds and adjusted behavior parameters, to simulate reduced traction and longer stopping distances.

Five key indicators were selected to evaluate the intersection's performance: average vehicle delay, queue length, number of stops, travel time, and LOS. These indicators provide a comprehensive analysis of the intersection's operation in terms of operational efficiency, congestion levels, and the quality of service provided to users.

4 Results

Following the simulation of the three scenarios presented above, for a cycle interval of 3600 s. To account for the stochastic nature of microscopic-level simulation models and to ensure the statistical stability of the results, a total of five simulation runs were performed for each scenario. The following values of the service parameters were obtained: maximum travel time, average travel time, average ($\overline{d}_{\text{dir}}$) and maximum delay ($d_{\max}$), as well as the average ($\overline{L}_{\text{q}}$) and maximum ($L_{\text{q}}^{\max}$) queue length, along with the number of stops (N_{stops}). From Figs. 4 and 5, it can be observed that in Scenario 2, the maximum and average travel time are improved on the priority roads within the intersection, while for the others these parameters show a clear degradation of up to 16 times in the case of maximum travel time, respectively up to 13 times in the case of average travel time. The same observations can be made for the average and maximum delay, where variations of up to 15 times can be observed (Figs. 6 and 7).

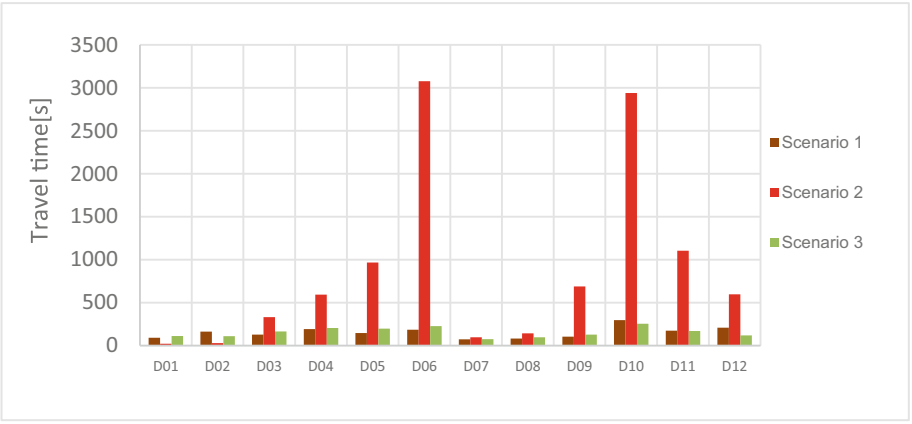

Fig. 4. Maximum Travel Time per direction and scenario

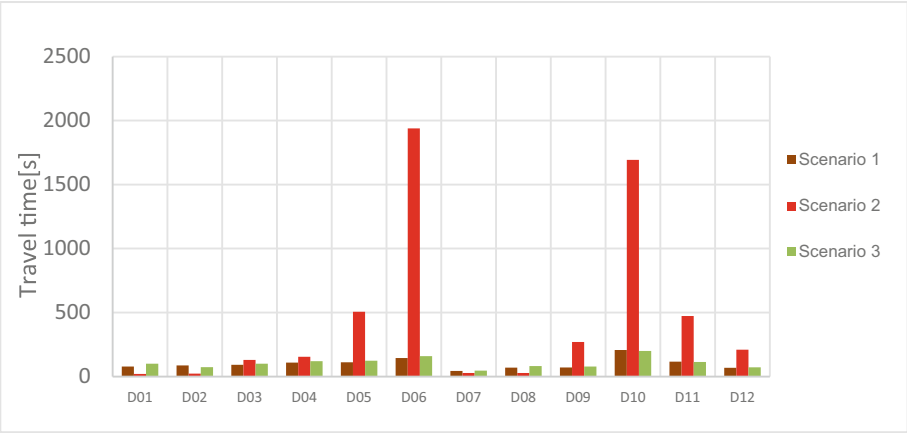

Fig. 5. Average Travel Time per direction and scenario

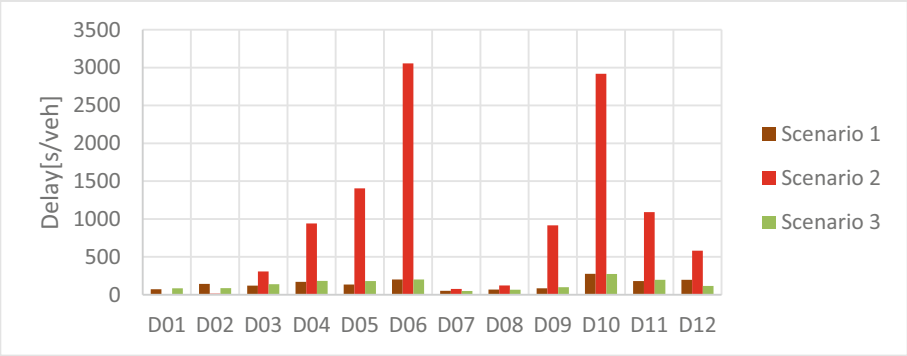

Fig. 6. Maximum delay per approach (s/veh)

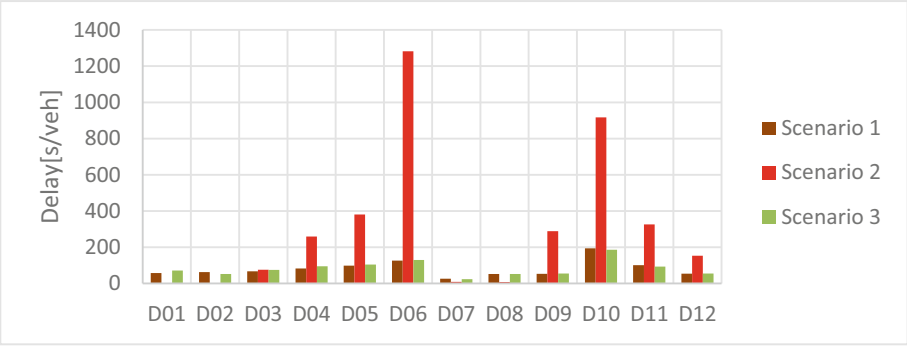

Fig. 7. Average delay per approach (s/veh)

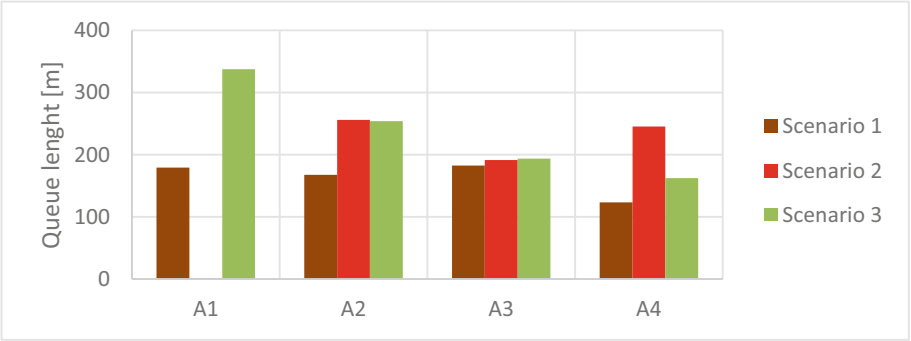

Fig. 8. Average queue length

In the case of the average queue length, as shown in Fig. 8, an increase is observed in Scenario 2, as expected, with the exception of the eastern direction, which, due to the low number of entities intending to turn left, sees most of the traffic moving along the priority east–west direction. Furthermore, the negative impact of adverse weather conditions, which leads to a reduction in vehicle speed at the intersection, is quantified by an increase in queue length in Scenario 3. The numerical values for the average and maximum queue length are presented in Table 3.

Table 3. Queue Length by Movement and Scenario

		Scenario 1			Scenario 2			Scenario 3		
Entry	Entry ID	$\bar{L}_q$ (m)	L_q^{max} (m)	N_{stops}	$\bar{L}_q$ (m)	L_q^{max} (m)	N_{stops}	$\bar{L}_q$ (m)	L_q^{max} (m)	N_{stops}
Blvd. Iuliu Maniu (East)	A1	179.22	248.18	6234	0.88	52.24	34	337.6	507.71	9224
St. Lujerului (South)	A2	167.53	184.25	4094	256.04	279.83	683	253.95	282.26	5611
Blvd. Iuliu Maniu (West)	A3	182.55	281.32	7056	191.48	406.34	4578	193.69	289.06	7359
Rd. Virtuții (North)	A4	123.17	141.57	1609	245.28	270.94	925	162.24	184.54	2240

Analyzing the intersection at a global level, regardless of the scenario, a Level of Service (LOS_{int}) E is identified, according to HCM standards (Table 1). However, as the level of analysis increases down to the level of each road converging into the intersection, it can be observed that this level (LOS_d) is not uniform across all approaches of the intersection. (Table 4).

Table 4. Intersection Level of Service by Direction and Scenario

	Scenario 1			Scenario 2			Scenario 3		
Direction ID	$\overline{d}_{dir}$ [s/veh]	LOS_d	LOS_{int}	$\overline{d}_{dir}$ [s/veh]	LOS_d	LOS_{int}	$\overline{d}_{dir}$ [s/veh]	LOS_d	LOS_{int}
D01	57.48	E	E	0.8	A	E	71.06	E	E
D02	63.06	E		2.12	A		52.51	D	
D03	66.7	E		75.49	E		74.85	E	
D04	82.46	F		259.26	F		94.69	F	
D05	98.07	F		380.63	F		104.14	F	
D06	126.04	F		1282	F		129.93	F	
D07	26.09	C		8.48	A		23.67	C	
D08	52.42	D		7.69	A		52.73	D	
D09	53.52	D		288.63	F		54.53	D	
D10	194.16	F		917.02	F		186.23	F	
D11	101.12	F		326.2	F		93.16	F	
D12	54.25	D		153.49	F		54.75	D	

Additionally, on the priority approaches within the intersection, the level of service in Scenario 2 may experience improvements, as is the case for the east–west movement direction. For Scenario 3, no variations are observed compared to the base Scenario 1.

5 Discussion and Conclusions

The simulation results show significant variability in operational parameters between traffic directions when traffic control system failures occur. In the flashing yellow light scenario (Scenario 2), the lack of traffic signal coordination leads to a significant decrease in performance on secondary access roads. This is particularly evident on directions D06 and D10, where average delays increased by over 900 s/veh compared to normal operation. These flows intersect directly with conflicting flows along the main east-west corridor, which explains the observed congestion.

In contrast, the directions along the main boulevard (D01, D03, D07, D09) show a slight improvement in traffic flow, due to the lack of restrictions regarding right-of-way. However, these advantages come at a cost, negatively affecting the efficiency of crossflow. This asymmetric behavior highlights the need for intersection-level regulation to balance the allocation of right-of-way.

It is interesting to note that, despite significant fluctuations in the directions, the overall LOS of the intersection remained constant at level E in all scenarios. This is because the HCM method combines the average control delay for all approaches, which masks the imbalances between directions. Therefore, the intersection-level LOS should be supplemented with performance indicators specific to each approach to highlight the operational effects of system degradation.

Scenario 3, which simulates winter conditions, shows a moderate decline in performance for all directions. Queue lengths increase due to reduced speeds and greater vehicle spacing, but not as much as they would increase due to the lack of traffic signal control. The operational degradation caused by environmental conditions remains more uniform and predictable than in the case of a control system failure, a fact confirmed by the simulation results.

Traffic-light-controlled intersections are a key component of urban transportation networks, as they are the points where both capacity and safety requirements converge. The analysis conducted in this study shows that changes in the traffic control system's operating mode, whether due to malfunctions or external conditions, can lead to significant variations in intersection performance.

Based on the microsimulation model developed in PTV Vissim, several operationally relevant scenarios were evaluated. The results highlight that, in the case of intermittent yellow light operation, the effects are not evenly distributed among traffic flows. The main directions may benefit from smoother traffic flow, but this advantage is offset by a marked deterioration in traffic conditions on the secondary directions, where congestion and significant delays occur. This disparity underscores the unbalanced nature of the intersection's operation in the absence of traffic signal control.

In contrast, the scenario simulating winter conditions leads to a general decline in performance, affecting all access points. Reduced speeds and changes in driver behavior result in a decrease in the intersection's evacuation capacity and, consequently, an increase in delays and queue lengths.

An important aspect highlighted by this research is the utility of microsimulation in analyzing situations that cannot be directly investigated under real-world conditions. The model allows for the reproduction of disruptive scenarios and provides a basis for quantifying their impact on operational indicators, in correlation with the HCM methodology.

From an applied perspective, the results can support the decision-making process in traffic infrastructure management by conducting ex-ante assessments of risk scenarios and identifying appropriate intervention measures. At the same time, the study highlights the need to integrate additional elements into simulation models, particularly those related to human intervention. In practice, traffic control by agents can significantly alter the behavior of traffic flows, an aspect not captured in the current form of the model.

This study also has several structural limitations. Human intervention (such as police traffic control), pedestrian flows, and adaptive traffic signal control were not modeled at this stage. The study assumed that traffic demand is constant across all scenarios, and sudden spikes in demand were not taken into account. Furthermore, this case study focuses only on operational indicators, without a direct quantification of the impact on safety.

Future work will extend the current study to include adaptive and resilient control mechanisms. Dynamic demand modeling and the inclusion of human-controlled traffic management in the event of failures will also be integrated. The use of real-time data and feedback from connected vehicles could enhance the robustness of predictive microsimulation models.

Disclosure of Interests. The authors have no competing interests to declare that are relevant to the content of this article

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