Analyzing the impact of motorcycle traffic on road congestion and vehicle flow

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ABSTRACT

Urban traffic systems are increasingly burdened by the rising prevalence of motorcycles, particularly in cities like Marrakech where they significantly influence traffic dynamics and congestion. This paper investigates the impact of motorcycle positioning on start-up lost time at signalized intersections, employing a comprehensive methodology that integrates real-world data collection and advanced simulation techniques. Using mobile phone cameras, traffic data were captured at key intersections, and the positioning and movements of motorcycles were analyzed using the YOLOv10 deep learning algorithm. These empirical data informed simulations carried out with the simulation of urban mobility (SUMO) tool to explore various motorcycle positioning strategies. The study reveals that motorcycles positioned close to cars exacerbate congestion, extending travel times and increasing queue lengths. Conversely, scenarios with dedicated motorcycle lanes demonstrate reduced congestion and smoother traffic flows. These findings highlight the critical role of strategic motorcycle positioning in enhancing urban traffic efficiency and suggest that dedicated motorcycle lanes could significantly improve overall traffic management.

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1. INTRODUCTION

The burgeoning number of motorcycles in urban centers presents unique challenges and opportunities for traffic management systems. Despite their small size and high maneuverability, motorcycles exhibit traffic behaviors that differ significantly from those of larger vehicles, creating complex traffic patterns, particularly at intersections. These differences often exacerbate traffic congestion and increase safety risks, especially in signalized intersections where interactions between motorcycles and other vehicle types are more pronounced. Existing traffic management strategies, while effective for larger vehicles, often fail to adequately address the unique dynamics introduced by motorcycles [1].

To date, research has focused on general traffic flow or the impact of motorcycles on safety, leaving gaps in understanding their role in traffic dynamics at intersections [2]. Addressing this gap, this study aims to investigate the strategic integration of motorcycles at signalized intersections, with the specific goal of minimizing start-up delays and improving both traffic fluidity and safety. By examining the placement of motorcycles at a key intersection in Marrakech, this research proposes data-driven solutions for optimizing urban traffic systems [3].

In this study, we tackle a significant challenge in urban traffic management: the strategic placement of motorcycles at signalized intersections in Marrakech. Our goal is to quantify start-up delays and enhance both the fluidity and safety of intersection traffic. Confronted with the initial shortage of empirical data, we employed mobile phone video recordings at a crucial intersection as our primary data collection method. These recordings were analyzed using cutting-edge computer vision technologies. With this dataset in hand, we conducted a series of traffic simulations using the simulation of urban mobility (SUMO) software to test various traffic configurations.

The paper is organized into four main sections following the introduction. In section 2, "Related Works," a comprehensive review of existing literature on vehicle start-up times and traffic dynamics is presented, highlighting key studies and identifying gaps that this paper aims to address. Section 3, "Methodology," details the data collection and analytical techniques employed, including the criteria for selecting study times and the process for measuring start-up delays. Section 4, "SUMO Simulation," describes the simulation environment and parameters used to model traffic scenarios and validate the empirical findings. The paper concludes with a summary of the key insights, implications for traffic management, and suggestions for future research directions.

2. RELATED WORK

In recent years, the growing prevalence of motorcycles in urban traffic systems has sparked considerable research interest, given their significant impact on traffic flow, safety, and environmental outcomes. This segment of related work consolidates a diverse range of studies that explore the dynamic role of motorcycles in various urban contexts. The compilation includes investigations into the modeling of motorcycle behavior, assessments of traffic safety and efficiency, and evaluations of policy measures aimed at integrating motorcycles more effectively into the broader transportation framework. Through a synthesis of simulation studies [4], field data analyses, and technological interventions, this section presents a comprehensive overview of how motorcycles influence and are influenced by the complex interplay of urban traffic elements. The aim is to provide a grounded understanding that supports the development of targeted traffic management strategies and infrastructure improvements to accommodate the increasing dominance of motorcycles in urban landscapes [5], [6].

This paper synthesizes a variety of studies focusing on the impact of motorcycles on urban traffic flow and safety across different regions. Initially, SUMO simulations reveal how motorcycle mobility affects vehicular traffic dynamics, with a focus on environmental and traffic efficiency outcomes [7]. Concurrently, the adoption of electric motorcycles is investigated for its potential to reduce traffic noise, with varied results depending on urban area characteristics [8].

In Indonesia, where motorcycles dominate traffic, studies have identified significant shortcomings in traditional traffic models, particularly their inability to account for motorcycle-specific behaviors. To address this, recent research has proposed a novel methodology for calculating saturation flow by integrating motorcycle dynamics, aiming to enhance traffic management at signalized intersections [9]. Further advancing this effort, scholars have employed cellular automaton models to simulate motorcycles' unique "lane-changing" behaviors, demonstrating their disruptive impact on overall traffic flow and advocating for infrastructure adaptations such as dedicated motorcycle lanes [10]. Complementing these findings, additional studies have introduced motorcycle car units (MCUs) to refine saturation flow analysis, underscoring the distinct traffic patterns in regions where motorcycles prevail [11], [12].

Similarly, in Thailand, researchers have investigated the factors influencing motorcycle riders' decisions to stop at urban signalized intersections, leveraging unmanned aerial vehicles (UAVs) for precise data collection [13]. Through multinomial logistic regression analysis, these studies pinpointed key determinants-such as intersection design and traffic density-that explain nearly 50% of the variability in riders' stopping behaviors, offering actionable insights for policymakers [14]. Beyond behavioral studies, broader examinations of motorcycle traffic's urban impact employ agent-based simulations to replicate real-world traffic scenarios[15] and computer vision systems to detect and reduce violations, highlighting technology's role in improving compliance and safety [6].

The challenges of motorcycle-dense traffic are further evident in cities like Hochiminh, where severe congestion has spurred calls for expanded public transport infrastructure to mitigate reliance on motorcycles [16]. Meanwhile, geographic information systems (GIS) and structural equation modeling (SEM) have elucidated motorcycles' multifaceted influence, from disrupting traffic flow in mixed conditions to shaping transportation perceptions in tourist hubs like Kuta, Bali [17], [18]. These findings emphasize the complexity of urban traffic systems in Southeast Asia, where interactions between motorcycles, cars, and pedestrians significantly alter speeds and safety outcomes [19]. Ultimately, there is a pressing need for updated traffic models that accurately capture the heterogeneity of urban mobility in developing megacities, where diverse transport modes coexist. Such models must prioritize both safety and efficiency, addressing the unique challenges posed by high motorcycle volumes while balancing the demands of other road users [20], [21].

In [22] study investigates how a high prevalence of motorcycles affects traffic flow and congestion in Marrakech, focusing specifically on the start-up lost time at signalized intersections. The research involves a twofold approach: initially collecting empirical data using computer vision techniques, particularly mobile phone video recordings at key intersections during different times. These videos were analyzed using the YOLOv8 [23] algorithm to track motorcycle positioning accurately. Following the data collection, VISSIM [24] simulations were employed to test various traffic scenarios, including mixed vehicle lanes and dedicated motorcycle lanes. Findings indicate that motorcycles positioned close to cars exacerbate congestion and extend travel times, while dedicated motorcycle lanes tend to mitigate these issues, enhancing overall traffic efficiency and safety at intersections.

While the study presented on the impact of motorcycle traffic in Marrakech provides insightful findings, there are certain limitations that merit consideration. Primarily, the use of the YOLOv8 algorithm for object detection raises concerns regarding accuracy. Although YOLOv8 is known for its real-time processing capabilities, it can sometimes struggle with detecting small or overlapping objects, which are common in dense urban traffic scenarios. This could lead to inaccuracies in identifying motorcycle positions, especially when they are closely interspersed with cars or other vehicles.

Another study that examines motorcycle behavior at urban intersections, while innovative, also exhibits significant limitations due to its reliance on simulated rather than real traffic data. The absence of empirical data could lead to a gap in understanding actual motorcycle behaviors under varying traffic conditions and during different times of the day. Simulated data often fails to capture the spontaneous decisions and maneuvers of riders, such as sudden lane changes or varied responses to traffic signals, which are crucial for accurate behavioral analysis. Additionally, the lack of real-world validation means that any proposed traffic management solutions may not be as effective when implemented in actual scenarios.

3. METHOD

In this study, we utilized the simulation of urban mobility (SUMO). This was chosen for this study due to its open-source nature, scalability, and ability to model complex traffic scenarios with precise vehicle behavior. It was used to analyze the impact of motorcycle positions on urban traffic flow [25]. Our methodology involved creating multiple traffic scenarios, each with varying numbers of motorcycles and different positioning strategies. Initially, we designed a base scenario with a standard mix of vehicles, including cars, buses, and motorcycles, to establish a control model. Subsequently, we incrementally increased the number of motorcycles in each scenario to observe the resulting changes in traffic dynamics. To ensure a comprehensive analysis, we considered several positioning strategies for motorcycles, such as lane splitting, riding in dedicated motorcycle lanes, and integrating with general traffic. For each scenario, key traffic parameters, including average speed, traffic density, and travel time, were recorded and analyzed. This approach allowed us to systematically evaluate the effects of motorcycle positioning and density on overall traffic performance, providing insights into potential traffic management strategies for urban environments.

3.1. Data collection

To ensure the accuracy and reliability of our simulation results, we decided to collect real traffic data to understand the behavior of motorcycles and other vehicles at intersections. We deployed two cameras at a busy urban intersection. The first camera was strategically positioned to count and detect the type of vehicles, categorizing them into motorcycles, cars, buses, and other relevant types. The second camera focused on capturing the start-up lost time for each vehicle type, particularly at the moment when the traffic light turns green. This setup allowed us to gather precise data on the reaction times and acceleration patterns of different vehicles. By analyzing the start-up lost time, we could identify any delays or inefficiencies caused by the presence of motorcycles or other vehicles. To ensure the accuracy of the collected data, careful calibration of the cameras was conducted prior to deployment, and the recording times were synchronized to avoid discrepancies. This real-world data was then used to validate and refine our simulation scenarios, ensuring that they accurately reflect actual traffic conditions and behaviors. This dual-camera approach provided comprehensive insights into vehicle interactions at intersections, enhancing the robustness of our study's findings.

Figure 1 illustrates the chosen location for data collection, highlighting the positions of the two cameras used in our study. The black point (A) is situated close to the signalized intersection, specifically positioned to calculate the start-up lost time for each motorcycle and other vehicles. This placement ensures accurate measurement of the reaction times and acceleration as vehicles begin to move when the traffic light turns green. The red point (B) is strategically located to count the vehicles entering the intersection, allowing us to calculate the traffic flow. This camera captures all incoming traffic, providing essential data on the number and types of vehicles, including motorcycles, cars, and buses. Together, these two points enable us to gather comprehensive data on both vehicle behavior at the intersection and the overall traffic flow, facilitating a detailed analysis of traffic dynamics and the impact of motorcycle positioning.

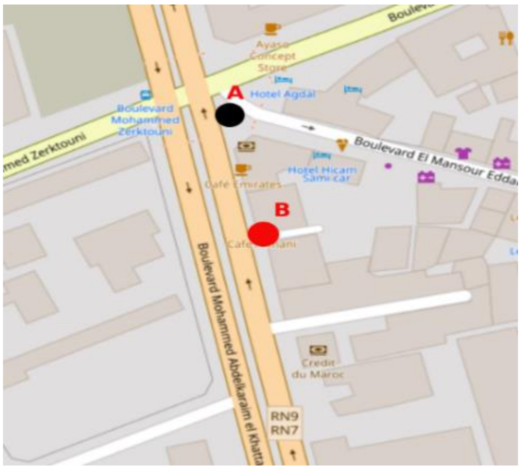

Figure 1. Illustration of research site and camera placement

3.2. Data analytic

Following the collection of traffic data, we conducted a detailed analysis to evaluate the start-up lost time for each vehicle. This process involved counting vehicles and detecting the start-up lost time sequentially for the first vehicle, the second vehicle, the third vehicle, and so on, as they moved through the intersection. To accurately identify and track each vehicle and the traffic light status, we employed the YOLOv10 [26] algorithm, a state-of-the-art object detection model known for its high precision and real-time performance. YOLOv10 allowed us to effectively detect various types of vehicles and traffic lights in the collected video footage. By leveraging this advanced detection capability, we could precisely measure the start-up lost time for each vehicle as they responded to the traffic signals. This analysis provided us with crucial insights into the delays and acceleration behaviors of different vehicle types, enabling a thorough understanding of the impact of motorcycle positioning on intersection performance.

Figure 2 presents the architecture for our data analytic process. The process begins with the preprocessing of video data, which involves preparing the raw video footage for analysis by enhancing image quality and extracting relevant frames. This preprocessed video is then fed into the YOLOv10 model, an advanced object detection algorithm.

The YOLOv10 model serves as the foundation for object detection, accurately identifying and localizing key elements within the video footage, including vehicles (such as motorcycles, cars, and buses) and traffic lights. Building upon these detections, the ByteTrack algorithm [27] is employed to track the movement of these objects across consecutive video frames, ensuring consistent identification and reducing errors caused by occlusions or temporary disappearances. This combined detection and tracking approach maintains continuity in object trajectories, which is essential for reliable traffic analysis. Simultaneously, the system classifies the detected objects into specific vehicle categories (e.g., motorcycles, cars, buses) and traffic signals. For traffic lights, an additional color detection module analyzes their current state (red, yellow, or green), a critical step for evaluating start-up lost time at signalized intersections. This multi-stage processing pipeline enables comprehensive traffic behavior analysis by integrating detection, tracking, classification, and signal state recognition into a cohesive framework.

The tracked objects, along with their classification and color detection data, are then used to generate several outputs. The draw tracking trails output provides visual tracking trails for each detected object, illustrating their movement paths. The video output is an annotated version of the original video, showcasing the detected objects and their classifications in real-time.

Start-up lost time is a critical metric in intersection performance analysis, measured by evaluating the delay between a traffic light turning green and the moment each vehicle begins moving. This calculation is achieved by precisely correlating the traffic light's state (detected via color recognition) with the movement patterns of tracked vehicles (monitored through ByteTrack). The resulting data provides valuable insights into driver reaction times and behavioral differences across vehicle types (e.g., motorcycles typically exhibit faster response times than larger vehicles), highlighting how vehicle composition affects intersection efficiency. Furthermore, this analysis enables comparative studies of start-up lost time across various traffic conditions, revealing how factors like vehicle mix, intersection design, and traffic volume influence driver responses. By quantifying these delays, transportation planners can identify problematic intersections and implement targeted improvements to reduce congestion and enhance traffic flow. The integration of computer vision (YOLOv10) with advanced tracking (ByteTrack) creates a robust framework for objectively assessing these traffic dynamics at scale.

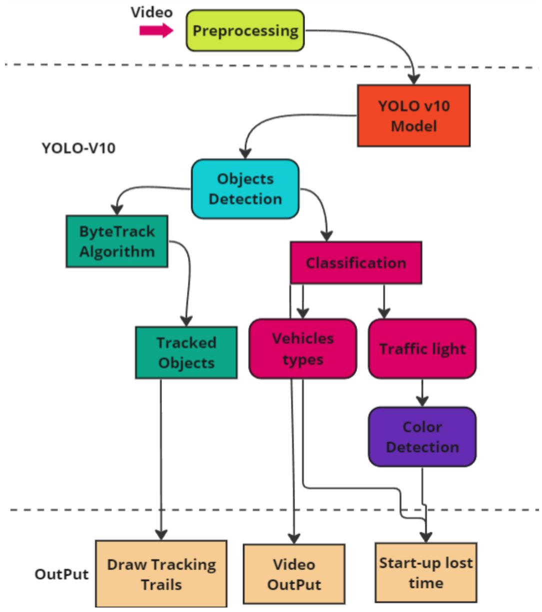

Figure 2. Analyzing traffic dynamics and start-up lost time at intersections: A comprehensive study using YOLOv10

3.3. Simulation scenarios

In the section dedicated to simulation scenarios, the methodology was structured to comprehensively evaluate traffic dynamics under various conditions. The simulations were meticulously designed to reflect real-world traffic situations, with data captured during key time intervals: 10:00-10:30, 12:00-12:30, 15:00-15:30, and 18:30-19:00. Each of these time periods was subjected to a 5-minute simulation, ensuring a detailed and consistent analysis across different scenarios.

The study employed a series of carefully designed simulated scenarios to systematically investigate how motorcycle positioning and density influence traffic flow dynamics. As illustrated in Figure 3, these simulations encompassed: (1) varying motorcycle penetration rates from 20% to 80% of total traffic volume, (2) different spatial distributions including clustered and dispersed formations, and (3) multiple lane configurations with and without dedicated motorcycle lanes. Each scenario was developed to isolate specific behavioral patterns, such as motorcycles' tendency for lateral filtering or queue-jumping at intersections, which are particularly relevant to Southeast Asian urban contexts.

3.3.1. Motorcycles positioned in front of cars and between lanes

In SUMO, this scenario can be configured by programming motorcycle entities to recognize and utilize the space available between lanes. The simulation allows motorcycles to filter through stationary or slow-moving traffic, moving towards the front of the queue at intersections. This is typically achieved by setting specific routing decisions and lane change parameters that are more aggressive for motorcycles compared to cars. The potential impact on traffic flow includes reduced wait times for motorcycles and possibly improved overall intersection efficiency. However, it also requires careful calibration to accurately model the riskier maneuvers associated with lane-splitting.

3.3.2. Motorcycles searching for a place in front of all cars

This setup involves configuring the SUMO parameters to prioritize motorcycles moving to the most advantageous position at traffic stops, typically the front of the queue. This could be accomplished by adjusting the desired speeds and lane-changing behavior to be more aggressive during slower traffic conditions, particularly as vehicles approach red lights or stop signs. The rationale is to simulate the behavior of motorcyclists in many urban environments, where they tend to advance to the front to minimize their wait time and accelerate quickly when the light turns green.

3.3.3. Motorcycles positioned between cars

Unlike scenarios where motorcycles are at the front or in a dedicated lane, this configuration involves motorcycles mixed within the car traffic. This requires tuning the SUMO simulation to allow motorcycles to occupy the same space as cars, reflecting a less dynamic riding style that might be seen in less congested areas or where lane-splitting is illegal. This scenario's significance lies in its ability to model the behavior of motorcycles in standard traffic flow and evaluate the impact on safety and car traffic dynamics.

3.3.4. Motorcycles in a dedicated lane separate from cars

In this scenario, SUMO is configured to simulate a dedicated lane for motorcycles, separate from those used by cars. This can be represented by a special lane type exclusively for motorcycles, with its own set of rules and behaviors. The focus here is on the potential benefits of such an arrangement, such as reduced conflicts between cars and motorcycles, potentially lower congestion levels, and improved safety for motorcyclists. Challenges might include the implementation in real-world settings and the effects on car lanes, such as reduced space or increased congestion for cars.

3.3.5. Motorcycles in the same lane as cars

A conventional positioning scenario in SUMO, where motorcycles follow the same rules and behaviors as cars, without any special treatment or routing. This scenario is valuable for assessing how motorcycles affect the flow of traffic when they do not have the option to lane-split or move to the front of the queue. It provides insights into the integration of mixed vehicle types under typical traffic regulations.

3.3.6. Traffic without motorcycles (only cars)

Serving as a baseline scenario, SUMO only simulates car traffic without the presence of motorcycles. This scenario allows for a clear comparison of how traffic flow and congestion are affected by the absence or presence of motorcycles. It serves as a control to highlight the specific impacts that motorcycles have when they are included in the simulation scenarios.

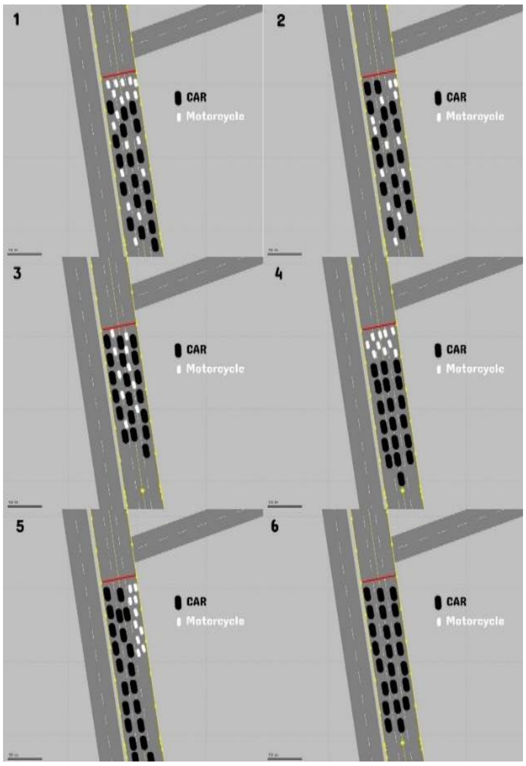

Figure 3. Traffic flow scenarios with varied motorcycles positions [28]

To calculate the average travel time from a simulation scenario that depends on start-up lost time, it is essential to consider several factors. These include the start-up lost time, the travel time under normal conditions, and any additional delays that might occur during the trip. By integrating these factors, you can accurately determine the overall average travel time for the scenario [29], [30].

4. RESULTS AND DISCUSSION

This section presents the results and discussion of our study, focusing on the impact of motorcycle positioning on traffic flow and start-up lost time at intersections. Through detailed simulations using SUMO, we analyzed various scenarios to understand how different motorcycle behaviors and interactions with other vehicles affect overall traffic dynamics. By systematically evaluating these scenarios, we aim to provide valuable insights into optimizing traffic management systems, enhancing intersection performance, and developing strategies to reduce congestion and improve safety for all road users. The following sections will detail our findings and discuss their implications for urban planning and traffic engineering.

Table 1 provides a comparative analysis of multiple traffic scenarios, evaluating their performance through four key metrics: travel time (s), average vehicle speed (km/h), stop-and-go events (frequency), and queue length (m). These parameters were selected to assess both traffic efficiency (via travel time and speed) and safety implications (through stop-and-go frequency and queue length). The comparison reveals how different traffic configurations-such as varying motorcycle densities, signal timings, or lane designs-impact overall intersection performance. By quantifying these relationships, the analysis offers actionable insights for urban planners seeking to optimize traffic flow while minimizing congestion and collision risks. For instance, scenarios with shorter queue lengths and fewer stop-and-go events typically indicate smoother traffic progression, whereas increased travel times may signal bottlenecks requiring infrastructure adjustments. This data-driven approach enables evidence-based decision-making for transportation policies in motorcycle-dense urban environments.

Table 1. The result of the sumo simulation

Scenarios	Time	Travel time (s)	Average speed	Stop-and-go events	Queue length (m)
Traffic without motorcycles (only cars)	10:00-10:30	54.89	49.25	3	41
	12:00-12:30	53.39	50	2	63
	15:00-15:30	57.49	35.8	2	38
Motorcycles in the Same line as cars	10:00-10:30	55.89	44	2	52
	12:00-12:30	54.39	51.8	3	78
	15:00-15:30	58.51	30.6	3	50
Motorcycles positioned between cars	10:00-10:30	56.82	38.9	6	45
	12:00-12:30	55.30	46.6	4	68
	15:00-15:30	59.49	25.5	5	42
Motorcycles searching for a place in front of All cars	10:00-10:30	57.80	33.7	3	44
	12:00-12:30	54.30	41.5	3	65
	15:00-15:30	54.40	27	3	45
Motorcycles in a Dedicated line separate from cars	10:00-10:30	58.89	28.6	4	39
	12:00-12:30	51.39	50.7	4	65
	15:00-15:30	57.49	15.17	2	32
Motorcycles positioned in front of cars and between lanes	10:00-10:30	59.80	23.45	5	50
	12:00-12:30	58.30	40.2	5	73
	15:00-15:30	60.30	12	6	40

When motorcycles share lanes with cars or are positioned between them, as observed in scenarios like "motorcycles in the same line as cars" and "motorcycles positioned between cars", there is a noticeable increase in travel times and stop-and-go events. For instance, during peak hours (18:30-19:00), travel times range from 58.44 to 60.44 seconds, indicating slower traffic flow and higher congestion compared to scenarios without motorcycles. Average vehicle speeds also decrease significantly, with speeds ranging from 20.6 to 21.7 km/h, highlighting the impact of mixed traffic on overall traffic efficiency. Stop-and-go events increase as well, varying from 4 to 7 instances per time slot, which reflects disrupted traffic flow and increased potential for accidents or delays. Queue lengths at intersections similarly extend, ranging from 69 to 92 meters during these peak periods, indicating prolonged waiting times and heightened congestion levels.

Conversely, scenarios where motorcycles have dedicated lanes, such as "motorcycles in a dedicated line separate from cars", demonstrate improved traffic conditions. In these scenarios, travel times are generally lower, ranging from 51.39 to 63.40 seconds across different time slots, indicating smoother traffic flow and reduced congestion. Average vehicle speeds are comparatively higher, ranging from 14 to 50.7 km/h, which signifies less disruption to traffic flow and improved efficiency. Stop-and-go events are fewer, ranging from 2 to 4 occurrences per time slot, indicating more consistent traffic flow and reduced potential for sudden braking or acceleration. Queue lengths at intersections are also shorter, ranging from 32 to 76 meters, suggesting minimized waiting times and improved intersection efficiency.

These findings are consistent with prior research that suggests dedicated lanes for motorcycles can improve traffic flow and safety. Studies like [30] have also shown that lane separation for motorcycles reduces congestion, particularly in urban environments where traffic density is high. However, our study extends this knowledge by examining specific motorcycle positioning strategies within simulations, offering a detailed look at how different behaviors, such as lane splitting and moving to the front of the queue, impact overall traffic dynamics. While the simulation model provided valuable insights, one limitation of the study is that it is based on synthetic traffic data and assumptions in the SUMO model, which may not capture all real-world complexities. Additionally, we encountered unexpected results when analyzing the "motorcycles positioned between cars" scenario, where the anticipated negative impact on traffic flow was less pronounced in certain cases, likely due to the specific traffic conditions during those time slots.

In summary, this study aimed to understand the effects of motorcycle positioning on traffic flow and start-up lost time at intersections, revealing the significant benefits of dedicated motorcycle lanes in urban settings. The findings emphasize the importance of considering motorcyclists' behavior when designing urban traffic systems to improve safety and efficiency. However, unanswered questions remain, particularly concerning how these results translate to real-world environments with varying traffic conditions and driver behaviors. Future research should focus on field studies and further simulations with additional variables, such as varying traffic signal timings and different vehicle types, to build on these findings and refine traffic management strategies for mixed-use environments.

5. CONCLUSION

This comprehensive study investigates the significant impact of motorcycle positioning on start-up lost time at signalized intersections in Marrakech, a city known for its complex traffic dynamics. Our research employs an integrated methodology combining: i) strategic field data collection at a representative intersection using mobile video recording across four critical time periods (morning peak, midday off-peak, evening rush, and weekend conditions) to capture varying traffic patterns; ii) advanced computer vision analysis through the YOLOv10 algorithm for precise detection and tracking of motorcycle positioning behaviors; and iii) traffic microsimulation using SUMO to validate findings. This multi-method approach provides robust insights into how different motorcycle positioning strategies influence both intersection efficiency and safety, with particular attention to their effects on start-up lost time during signal phase transitions. The combination of empirical observation and simulation modeling ensures the reliability and practical applicability of our findings for urban traffic management in motorcycle-dense environments.

Simulations in SUMO, informed by the collected data, evaluated traffic dynamics under scenarios ranging from shared lanes for motorcycles and cars to dedicated motorcycle lanes. Key findings reveal that when motorcycles are positioned closely between cars, traffic congestion increases, leading to longer travel times, reduced average vehicle speeds, more frequent stop-and-go events, and longer queue lengths. Conversely, scenarios incorporating dedicated motorcycle lanes consistently demonstrated reduced congestion and smoother traffic flow, emphasizing the benefits of motorcycle-car separation for optimizing traffic efficiency and road safety. This study contributes to the existing body of knowledge by offering empirical evidence of how motorcycle positioning impacts traffic performance at intersections. The findings highlight the critical role of dedicated motorcycle lanes in urban traffic management and provide actionable insights for urban planners and policymakers to enhance intersection efficiency and safety in densely populated cities.

Future research could extend this study by exploring the impact of motorcycle positioning under diverse environmental and infrastructural conditions, such as varying intersection designs, weather scenarios, and traffic densities. Investigating the integration of emerging technologies, such as connected vehicles and intelligent traffic systems, could further refine strategies for optimizing traffic flow. Additionally, a broader geographical analysis encompassing multiple cities with distinct traffic patterns would provide a more comprehensive understanding of these dynamics, contributing to globally applicable traffic management solutions.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

ETHICAL APPROVAL

This research did not require ethical approval as it did not involve human participants, animal experimentation, or sensitive personal data.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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