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Microscopic simulation-based optimization of signal timing for urban intersections: A case study from Kirkuk, Iraq

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Abstract
This research article presents the results of a study conducted in Al-Qadisyah, Kirkuk in Iraq to analyze the effect of improving signal cycle lengths on traffic performance and environmental impacts at a four-legged signalized intersection. The explorations included a microscopic simulation model (PTV VISSIM) using a stage-based signal controller to study several cycle lengths (60-120 seconds) as means to improve signal performance. There was a significant improvement when the cycle length was reduced to 60 seconds versus the original cycle length of 120 seconds, thereby a cycle length of 60 seconds increased traffic performance, expressed as an average que length decrease of 19.8% (from 129.96m to 104.20); vehicle delay decrease of 21.9% (from 117.54 s to 91.81 s); and fuel consumption decrease of 10.4% (from 93.02 to 83.38 US gallons). CO emissions decreased by 5% and NOx emissions decreased by 23%. The study indicated that the performance improvement from altered signal timing has great potential for intersection operation and improves the environmental effects of signal operation on urban traffic networks.

Keywords: Signal cycle optimization, microscopic traffic simulation, urban intersection performance, vehicle emissions, PTV VISSIM

1. Introduction

1.1 Background

The effective regulation of urban transport systems in metropolitan areas relies heavily on accurate traffic signal control and coordination to move efficiently and in an orderly fashion. Signalized intersections are crucial in minimizing automobile and pedestrian conflict at intersections, maintaining a level of safety to individuals while optimizing an efficient vehicle flow in highly congested urban zones [1-3]. Signalized intersection points are hypothesized to be a bottleneck as poorly timed signals may have a large impact on overall system performance. Cycle length, which is defined as the total time for all signal phases to run, is one element of efficient and effective signal operation. If a cycle length is too short, the signal may not meet traffic demand, resulting in too many phase changes and lost start-up times. However, if a cycle length is too long, there may be excessive interruption in waiting times, excessive queue lengths, and ineffective green times for each of the approaches [4-6].

Historically, cycle lengths for signals have been derived using some analytical method, most prominently Webster's formula, that seeks to optimize delay and capacity. Although analysts can create theoretical limits, they disregard changing traffic levels, changing demand levels, or the environmental externalities of emissions and fuel consumption related to vehicles. Additionally, most urban intersections in most developing countries, including Iraq, still use fixed-time plans for signals which have not been optimized through data collection that remedy the concern of congestion and pollution, especially during peak hours [7, 8].

In recent years, microscopic traffic simulation has emerged as a highly informative tool for analyzing and evaluating signalized intersections. Simulation tools such as PTV VISSIM can accurately model minute-by-minute trajectories of individual vehicles, behavior at conflict points, as well as the impact of signal control effects (parameters) under a variety of demand levels. As such, the tool can offer a high degree of fidelity in simulating alternatives involving different signal cycle lengths, the various phase plans, and control strategies, as well as compute or estimate the influence in terms of traffic parameters (average queue, vehicle delay), and for measures pertaining to the environment [9-11].

Recent developments in the domains of deep learning and sensor-based systems have emphasized the steadily increasing role of advanced computing models in real-time environmental and behavioral monitoring. For instance, Yalcin and Alisawi [12] implemented a systematic review about improving social interaction for those who are visually impaired through emotion recognition with smart glasses and deep learning, thus illustrating the possible enhancement of human mobility and human interaction using artificial intelligence-based tools in changing environments. Similarly, Nife and Chtourou [13] conducted a comprehensive evaluation of the performance of the neural network-like performance models, YOLO and RetinaNet, for the real-time task of object detection, weighing accuracy vs. computation. This can be attributed to the fascination surrounding the practical application of advanced learning algorithms in transport and design systems

The significance of signal cycle length is not only about operational efficiency. From an environmental standpoint, longer signal cycles are perhaps generally associated with more stops, a loss of time in idling, and delays, whereby leading to emissions from motor vehicles carbon monoxide (CO) and nitrogen oxides (Nox). These emissions are indicators of urban air quality and public health issues. Additionally, inefficient traffic operations lead to wasted fuel and wasted economic and environmental resources [14, 15].

1.2 Problem Statement

In most urban areas, such as Kirkuk, Iraq, long cycle-length, fixed-time signal plans are employed without considering the dynamics of the location. Al-Qadisyah's four-leg signalized junction runs under a static cycle length of 120 seconds, which might now be outmoded based on prevailing traffic demand and stream characteristics. Preliminary field observations and literature indicate that lengthy cycle times will promote increased vehicle delays, queue length, fuel consumption, and emissions of harmful pollutants by maintaining red phases and inefficient release patterns for extended durations.

While international best practices for traffic signal optimization have evolved, there are few, if any, studies that research the effects on operations and the environment of cycle length modification in Iraq's urban environments through high-resolution simulation techniques. This is a gap that hinders traffic engineers and urban planners from making evidence-based upgrades to infrastructure.

1.3 Research Contribution

This research overcomes the above shortcomings by undertaking a comprehensive microscopic simulation study of the Al-Qadisyah junction of Kirkuk using the PTV VISSIM model. The study evaluates variations in how different cycle lengths between 60 and 120 seconds (increments of 10 seconds) affect various performance measures such as average queue length, average delay, CO and NOx emissions, and volume of fuel consumed.

The principal contributions of this research are as follows:

- Providing empirical evidence that shorter signal cycle lengths (especially 60-90 seconds) significantly improve traffic operation while reducing the environment impacts.
- Providing evidence of PTV VISSIM as an approach to optimally control some traffic signals for a Middle Eastern context.
- Providing a model of simulation that would facilitate further development, spatially influenced signal timing at respective intersections in developing countries.

The contribution of this research to traffic management practices, in respect to improving sustainability and operating effectively at urban intersections, is both academically and practically relevant as it addresses regional knowledge gaps and presented actionable outputs.

2. Literature Review

The issues surrounding the signal timing optimization process at urban intersections have been acknowledged in traffic engineering as operational performance of the total roadway system (in terms of traffic flow, safety, and environmental) for some time. The optimization issues have been compounded by the continuing urbanization and the higher demand for automobile travel, and creates issues that are more than what a fixed-time signal program can usually address to variations in the traffic stream, especially when the location is new or congested [16, 17]. Developments in traffic simulation and computational algorithm techniques have enabled researchers to examine new signal timing optimization methods, involving multi-agent systems, stochastic optimization, swarm intelligence, and real-time control schemes, many of which are tested in microsimulation environments such as PTV VISSIM [18, 19].

Table 1 provides a summary of selected studies that employed optimization and simulation methods to facilitate better traffic signal strategies for different urban environments. Their studies, which consisted of single signalized intersections to large-scale network-based approaches, documented a decrease in delay, queue length, travel time, and emissions. The findings of these studies acted as a sound foundation for the present research into the optimization of signal cycle time in Kirkuk, Iraq.

Table 1: Summary of Key Studies on Signal Timing Optimization Using Microsimulation and Algorithmic Approaches.

Study	Focus	Study Area	Methodology	Key Findings
[20] (2018)	Microscopic simulation using multi-agent system to optimize signal timing	Tianjin intersection	Multi-agent simulation	Improved traffic efficiency significantly
[21] (2019)	Bi-objective stochastic simulation-based optimization (BOSSO) for equity and efficiency	Urban network	Stochastic simulation and regression models	BOSSO outperformed others; enhanced efficiency and equity
[22] (2019)	MIMO control model for signal timing across large-scale intersections	Networked intersections	High matrix MIMO modeling	Reduced travel delay and improved energy efficiency
[23] (2020)	Stochastic optimization using SPSA algorithm for traffic signal design	Urban signalized intersections	Microsimulation with SPSA and GA comparison	SPSA outperformed GA with faster convergence
[24] (2021)	Swarm intelligence algorithm to reduce congestion through signal timing	Urban intersections	Swarm intelligence optimization	Delay reduced by 10.25%, stops by 24.55%
[25] (2022)	Micro-simulation based signal optimization in Makassar City	Makassar, Indonesia	Micro-simulation with trial-and-error calibration	Reduced queue length and delay
[26] (2023)	MOPSO algorithm for real-time multi-objective signal timing optimization	Smart intersections	MOPSO and decision-making algorithm	Delay reduced by 21.35%, capacity improved by 3.69%
[27] (2024)	VISSIM-based optimization of one-way traffic intersection	Xi'an	VISSIM simulation	Improved delay, queue, and travel time
[28] (2024)	Trajectory-based signal optimization using spatio-temporal data	Urban intersections	Simulation with vehicle trajectories	Outperformed Webster in delay and speed

Despite the large volume of research for signal timing optimization based on cutting-edge algorithms and microscopic simulation models, there are gaps within existing literature. Most of the existing research is done within well-developed urban areas that have real-time traffic data or on algorithmic performance without taking account of practical implementation limits for less developed areas. Little emphasis has been on assessing the immediate effects of changing signal cycle length especially by 10-second increments on traffic efficiency and environmental factors within individual intersections. Only a handful of studies directly explore countries such as Iraq, which face predominantly signalized intersections using static, antiquated timing plans with little semblance of systematic investigation, particularly through simulation programs, like PTV VISSIM. The gap in geography and methodology precludes the ability to move findings from other studies concerning international investigations into regional studies subject to varying traffic and infrastructure constraints.

The gap is assessed through a simulation using VISSIM, where the study evaluates cycle length parameterization in an experimental field site, which is a real-world four-leg intersection located in Al-Qadisyah, Kirkuk. The study changes cycle length parameters from 60-120 seconds, in 10 seconds increments, while assessing multiple physical impacts of congestion including average delay, queue length, fuel consumption, and emissions outputs, while also providing context-specific insights, which may lead to beneficial signal timing parameterization recommendations for similar urban corridors throughout the developing region.

3. Methodology

3.1 Methodology Overview

This research employs a simulation approach in order to examine the effects of cycle length on operational and environmental performance of a signalized intersection made up of four legs in the Al-Qadisyah section of Kirkuk, Iraq. The approach describes a methodical series of steps, from the planning of data collection and model building through the analysis of the simulation runs and their performance.

The first step involved the identification of the study focus area in addition to collecting the baseline geometrical, traffic, and signal/government control data (traffic volumes and factors, and the existing signals' time periods). The second step was to develop an accurate microscopic traffic model within the simulation environment of PTV VISSIM, as determined by the geometry, traffic movements, and control logic at the intersection level and stage-based signal programming.

As a subsequent step, the length of corresponding cycles of 60, 70, 80, 90, 100, 110, and 120 seconds were chosen for further examination. All scenarios were run with the same traffic demand to allow for a fair comparison of performance results. Some of the noteworthy performance measures sampled included average queue length, average vehicle delay, fuel consumption, and gas emissions (CO and NOx).

The study's method flow is depicted in Figure 1, which details the principal phases from the definition of the intersections to the interpretation of the results.

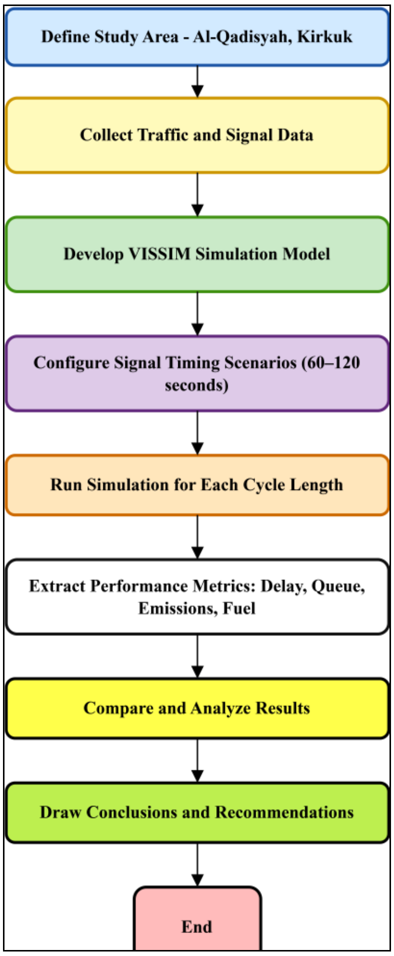
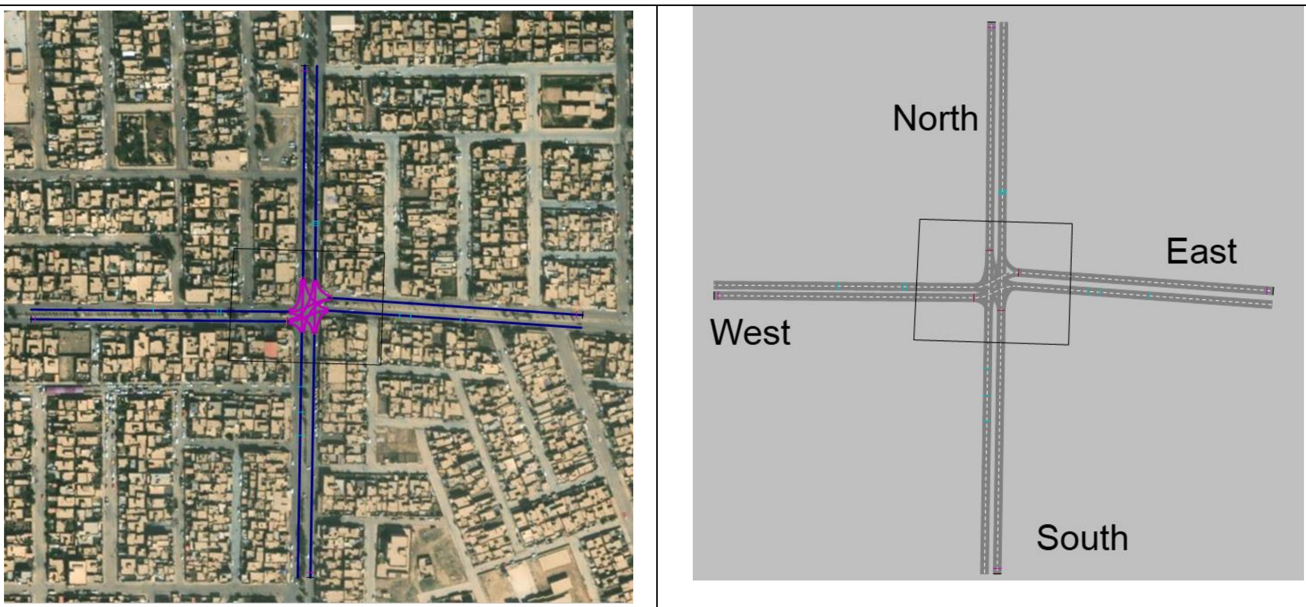


Fig 1: Methodological Flowchart of the Simulation-Based Cycle Time Optimization Study.

3.2 Study Area Description

The work is based on a four-leg signalized junction within the Al-Qadisyah district within the city of Kirkuk, Iraq as shown in Figure 2. This is an important urban junction that has residential and commercial land use nearby, and it suffers from significant congestion during peak hours. All legs provide customary urban traffic movements comprising through left, and right turns.

At present, the junction is under a plan using a fixed timing for its signal, which lasts for a total 120 seconds, equally distributed across the four phases. The signal plan has never been updated, despite clear traffic congestion and delays. Therefore, it is a suitable location for assessing the impacts of signal cycle optimization using traffic simulation at the microscopic level through PTV VISSIM.



(a) (b)

Fig 2: (a) Aerial view of the four-leg signalized intersection, (b) Modeled layout of the intersection in PTV VISSIM.

Due to security concerns and the absence of operational surveillance cameras in the study area, direct field data collection through video-based traffic counts was not feasible. As a result, the traffic volumes used in the simulation were estimated based on the typical cycle time duration and the intersection's observed capacity to handle flow under current conditions. The input traffic volumes were created to represent realistic vehicle movements per hour (vph) across all approaches taking into account the operational characteristics of the intersection. Table 2 displays the volumes of traffic selected for left turns, through movements and right turns in each direction.

Table 2: Hourly Traffic Volume by Movement and Approach

Approach	Left Turn (LT)	Through (TH)	Right Turn (RT)	Total Flow (vph)
Northbound	150	500	120	770
Southbound	130	480	140	750
Eastbound	180	520	160	860
Westbound	170	510	150	830

The current operation at this intersection uses a fixed-time signal control method characterized by a cycle length of 120 seconds with the green time being evenly split into four sections for the four approaches: North, East, South, and West. Each approach receives time of 25 seconds of green time,2 seconds of yellow (amber) phase time and 3 seconds of red clearance time. The signal sequence is carried out in stages with only a single direction of movement allowed to be green while the conflicting movement goes red thus ensuring that no conflicting movements happen at the same time. The stage-based signal arrangement demonstrated in the Figure 3 presents the timing plan that was implemented in the PTV VISSIM environment.

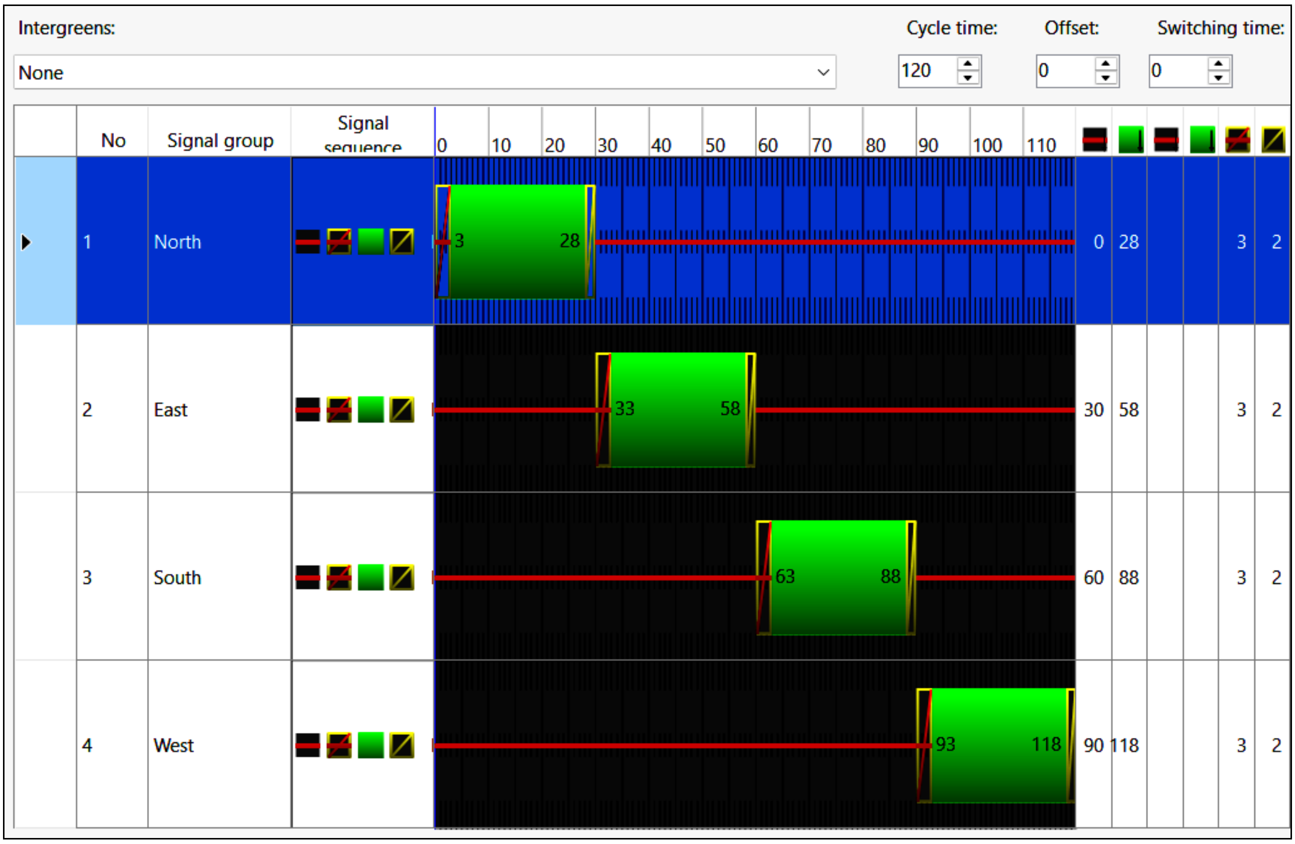
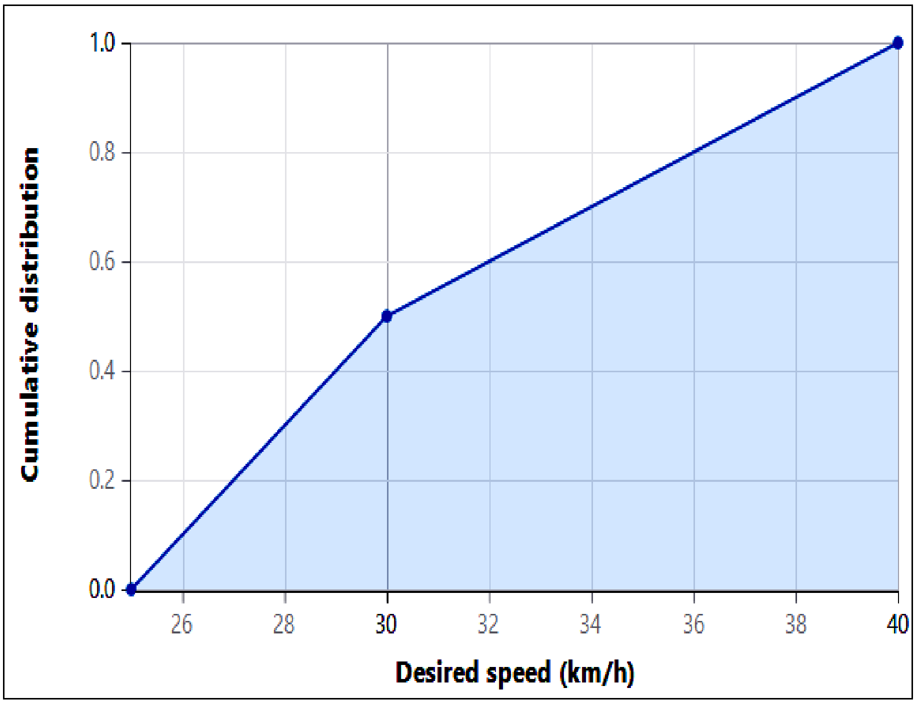
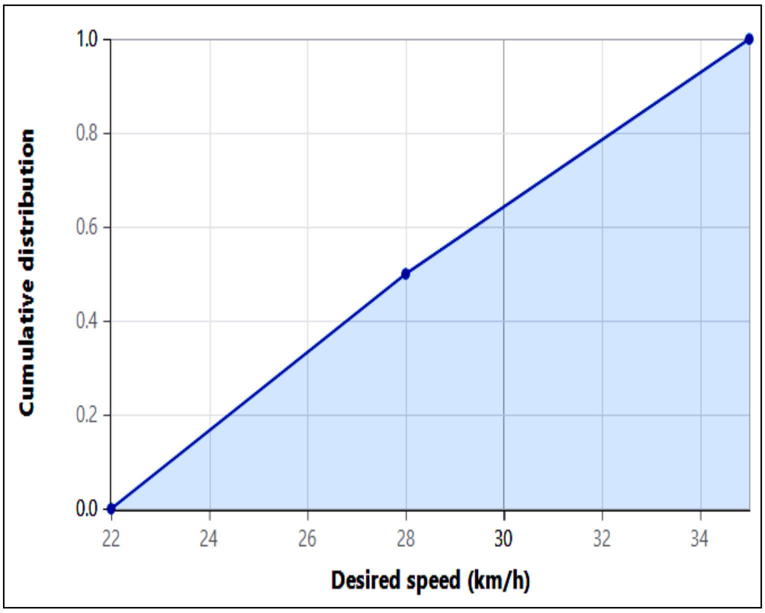


Fig 3: Stage-based Signal Timing Program for the Al-Qadisyah Intersection (Cycle Time = 120 seconds).

The various classifications of vehicles were assigned different, but realistic, desired speed distributions in the simulation model, to replicate realistic driving behavior across the network. All passenger cars, light goods vehicles (LGVs), and buses were modelled with some notion of desired speed based on a cumulative distribution curve. Figure 4(a) shows designated speeds of 25 to 40 km/h for passenger cars, consistent with typical urban driving conditions. LGVs were modelled with minimal speed ranges between 22 and 34 km/h (Figure 4(b)). Buses were anticipated to have desired speeds for a slower cumulative distribution of designated speeds in the range of 20 to 32 km/h, owing to their size and nature of frequent stopping for passengers, as shown in Figure 4(c). Cumulative distributions for each of these vehicle types assign a level of realism to the simulation behavior, while enabling desired speed variability and heterogeneity in vehicle behavior.



(a)



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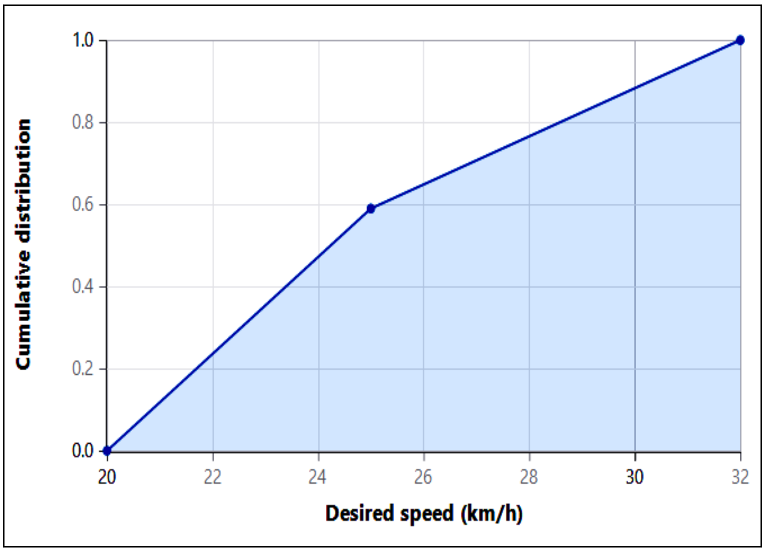

(c)

Fig 4: (a) Desired speed distribution for passenger cars, (b) Desired speed distribution for LGVs, (c) Desired speed distribution for buses.

3.3Vehicle Composition: With the aim to realistically depict the true traffic mix at the junction, the simulation model was developed to include three classes of vehicles, namely: passenger cars, light goods vehicles (LGVs) and buses. The traffic composition for each approach was established based on known distributions and then subsequently applied, as shown in Table 3. Each approach had a greater proportion of passenger cars varying between 80% and 85%, then followed by LGV (10% to 15%) and a minority proportion of buses (5%).

Table 3. Vehicle Composition by Approach in the Simulation Model.

Vehicle Type	Passenger Car	LGV (Light Goods Vehicle)	Bus
Northbound	0.85	0.1	0.05
Southbound	0.8	0.15	0.05
Eastbound	0.83	0.12	0.05
Westbound	0.84	0.11	0.05

Projected visuals of the types of modeled vehicles used for simulation are provided in Figure 5, which captures the range of vehicle class and shape as presented in the PTV VISSIM environment. These settings were implemented uniformly for each signal cycle scenario for the sake of outcome comparability.

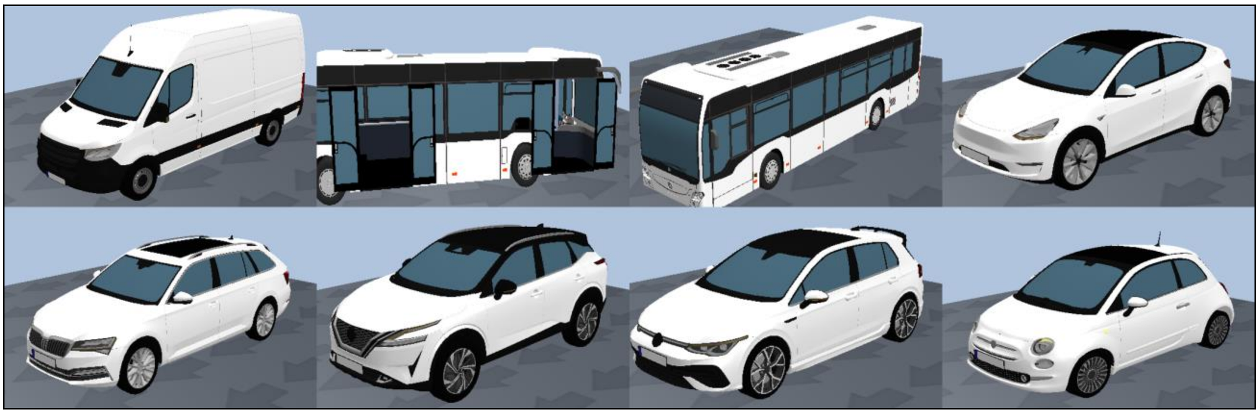

Fig 5: 3D Visualization of Vehicle Types Used in the VISSIM Simulation (Passenger Car, LGV, and Bus). Source PTV VISSIM Model.

3.4 Car-Following Model Configuration

The Wiedemann 74 car-following model was used to simulate longitudinal vehicle behavior for all vehicle types in this study. Parameter settings were adjusted for each vehicle class to reflect realistic driving characteristics. Passenger cars followed the default values typically used in urban simulations, while LGVs and buses were assigned larger standstill and safety distances to account for their size and brake needs. The complete set of parameters used in the simulation is summarized in Table 4.

Table 4: Car-Following Model Parameters for Different Vehicle Types (Wiedemann 74).

Vehicle Type	Model Used	Average Standstill Distance (m)	Additive Part of Safety Distance (m)	Multiplicative Part of Safety Distance
Passenger Car	Wiedemann 74	2	2	3
Light Goods Vehicle (LGV)	Wiedemann 74	2.5	2.4	3.6
Bus	Wiedemann 74	3	2.6	3.9

3.5 Signal Timing Optimization

PTV VISSIM does not employ an automatic algorithm for signal optimization in its standard interface. Rather, it provides users with the ability to manually optimize signal timings through trial-and-error microscopic simulation for a series of configurations. The optimization procedure is termed simulation-based, using trial-and-error simulation or the use of third-party optimization programs or control logic (e.g., Python API, COM interface, or applications VISTRO or VISVAP). A stage-based fixed-time controller was used directly within VISSIM for this research for modeling common field conditions and for evaluating on a systematic basis the effect on the intersection's performance due to changes in the cycle time.

The optimization method employed in this study employed a parametric simulation-based strategy, varying the total signal cycle length through seven discrete ranges: 60, 70, 80, 90, 100, and 110 seconds as shown in Figure 6. Proportionate green times within the four directions (north, east, south, and west) and constant intergreen times (all-red and amber phases) for each scenario were employed. The objective was neither to calculate an algorithmic optimal cycle length nor to find the most efficient fixed plan, but to compare the most efficient fixed plan through the performance metrics, i.e., vehicle delay, queue length, fuel usage, and emissions, for all configurations.

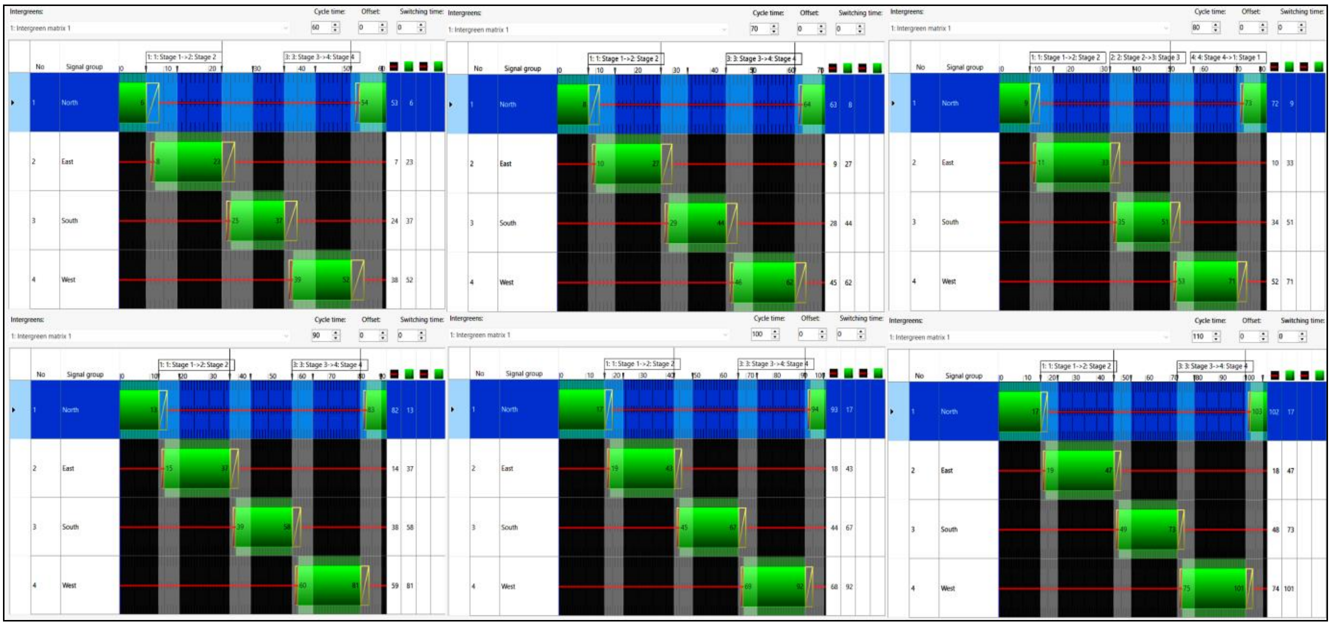

Fig 6: Fixed-Time Signal Plans for Cycle Lengths from 60 to 110 Seconds (Stage-Based Control in VISSIM).

3.6 Performance Measures

In order to assess the potential benefits of the signal timing alternatives, the four key performance indicators were examined in the current study:

- Average Queue Length (meters)
- Average Vehicle Delay (seconds)
- CO and NOx Emissions (grams)
- Fuel Consumption (US gallons)

The average queue length was quantified using the Queue Counter functionality incorporated in PTV VISSIM. This feature measures the spatial accumulation of vehicles along each approach, allowing for a reasonable assessment of average queue length over the simulation duration.

For the other indicator, vehicle delay, emissions, and fuel consumption - the data were obtained using the Node Evaluation functionality in VISSIM. A rectangular evaluation area node was identified along the outer section to cover the middle zone of the intersection capturing a comprehensive measurement of all relevant movements entering and existing the junction.

The criteria were deliberately selected to reflect operational effectiveness (delay and queue length) and environmental effectiveness (emissions and fuel use) in the overall assessment of the effectiveness of signal control with the selected cycle lengths.

4. Results

This section will describe the results derived from the simulation scenarios that were used to evaluate the impacts of optimized signal cycle length on operational and environmental impacts at the studied intersection. The cycle time was specifically varied from 60 seconds to 120 seconds, increasing by ten-second increments, and the performance measures considered were average queue length, delay time for vehicles, gas emissions (CO and NOx) and fuel consumption. All simulation scenarios were conducted under the same demand scenarios, and average results were provided as computed for the simulation horizon.

4.1 Impact of Cycle Length on Average Queue Length

Figure 7 illustrates the correlation between signal cycle length and average queue length. The results of the simulation indicate a direct correlation, observing longer average queues with longer cycle lengths. The average queue length of 104.20m occurred at the 60-second cycle length, while the average queue length of 129.96m was observed at the 120-second cycle length - an increase of approximately 19.8% in average queue length overall. The consistent increase is a result of the longer red phases, which create greater vehicle accumulation, especially during peak periods. While it is true that longer green times in each cycle lengthically allows more vehicles to move through the intersection, the total delay of prolonged red phases is greater than the small gain in mixed-flow queuing situations at times of maximum demand.

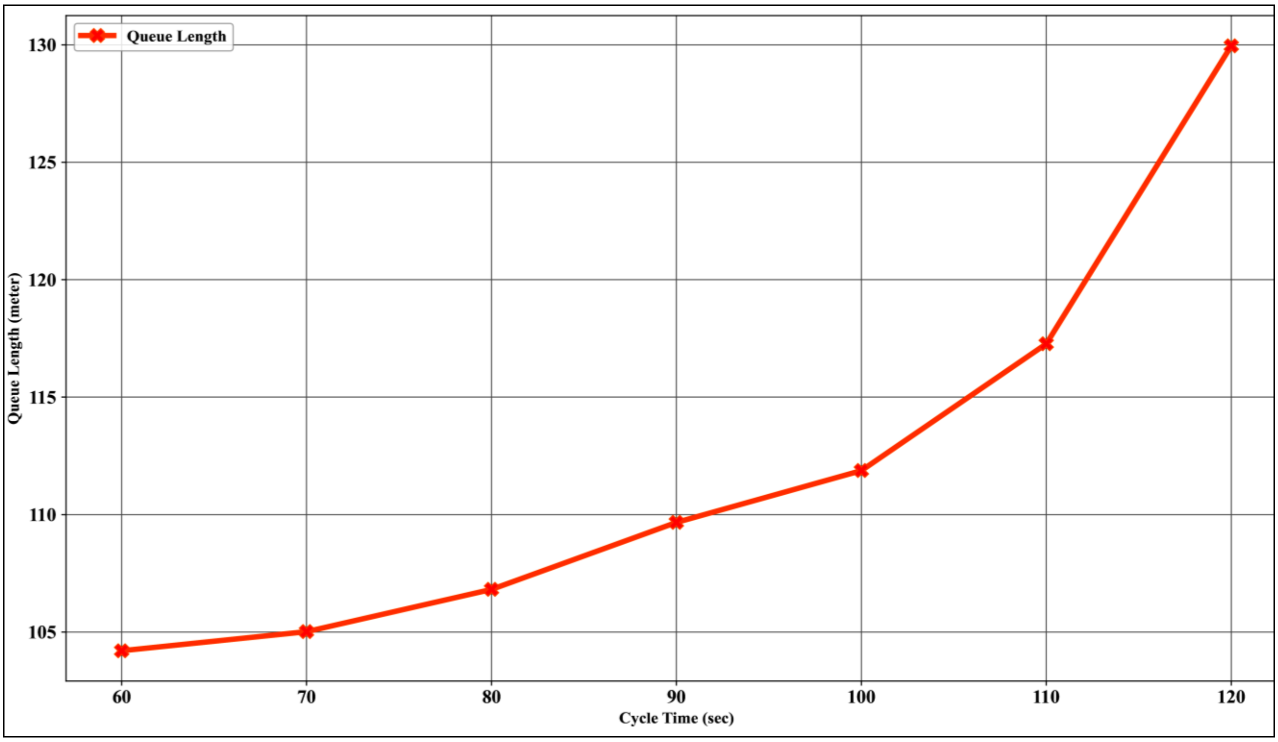

Fig 7: Variation of Average Queue Length with Different Signal Cycle Times.

4.2 Impact of Cycle Length on Average Vehicle Delay

As indicated in Figure 8, vehicle delay increases significantly with increases in the cycle length. At the 60-second cycle, the minimum average delay recorded was 91.81 seconds, whereas at a 120-second cycle, the maximum average delay was 117.54 seconds resulting in a delay difference of 25.7 seconds, or a 21.9 percent increase. This can be explained by the fact that a shorter cycle means a vehicle will have an opportunity to be served more frequently, thereby reducing the amount of time a vehicle is idle at the intersection. While longer cycles might service more vehicles in a single cycle, they individually contribute to more waiting time or longer time spent waiting for the cycle to end to receive a green signal from another approach when demands are unbalanced.

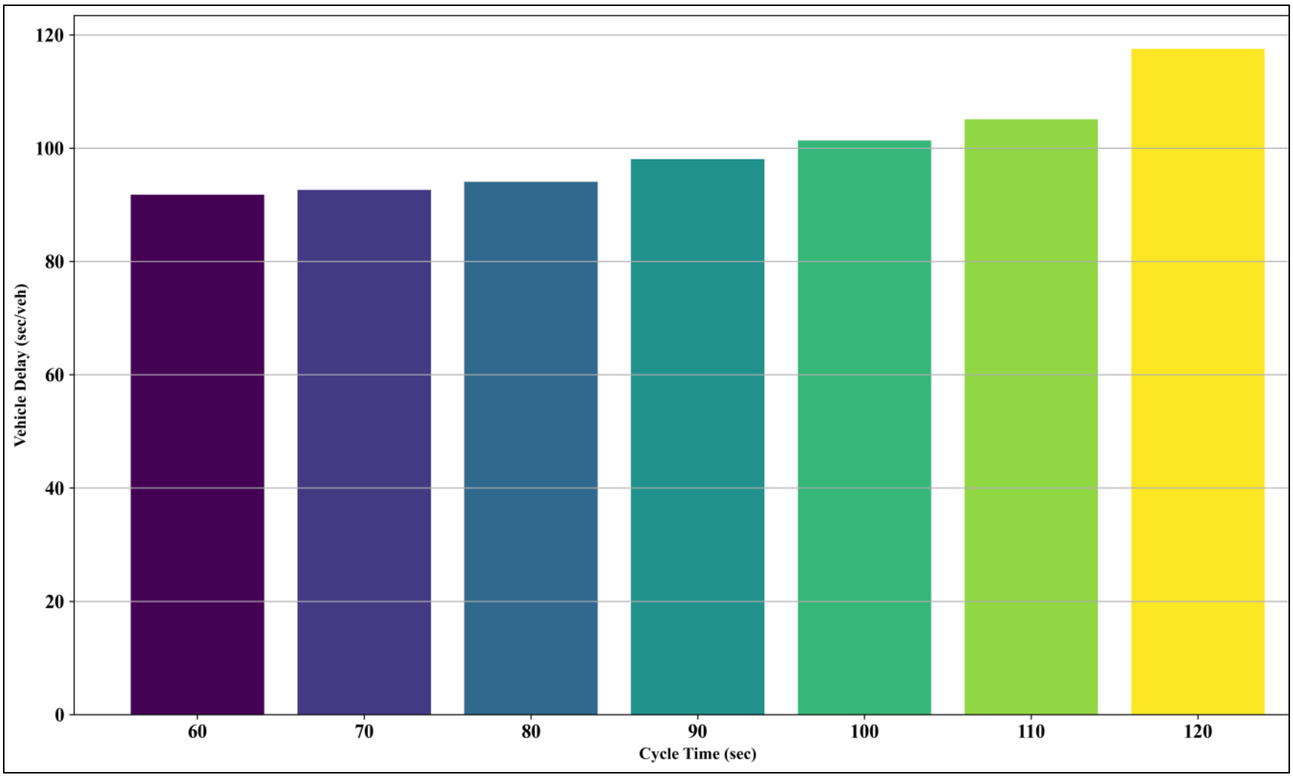

Fig 8: Effect of Signal Cycle Time on Average Vehicle Delay.

4.3 Impact of Cycle Length on Gas Emissions

Figure 9 presents a 3D visualization, depicting the relationship between the cycle time for the signal, CO, and NOx emissions. The data shows that both types of emissions increase with longer signal cycles. The CO emissions increased from 6177.84 grams at 60 seconds to 6502.07 grams at 120 seconds, for a net increase of 5% for CO emissions. In contrast, the NOx emissions exhibited an even greater increase from 1201.98 grams at 60 seconds to 1565.07 grams at 120 seconds, which shows a percentage increase of 30.2% for NOx emissions.

Reduced signal timing creates trends due to increased stopping and stopping and going behavior created by longer signal timing. The longer the signal timing, the more idling time, which may induce later vehicles to stay idle longer, indicating that they are not in optimal combustion mode: therefore, increasing emissions. The visual association shown in the 3D plot also confirms the earlier conclusion which shorter signal timing produced less CO emissions and superior traffic behavior.

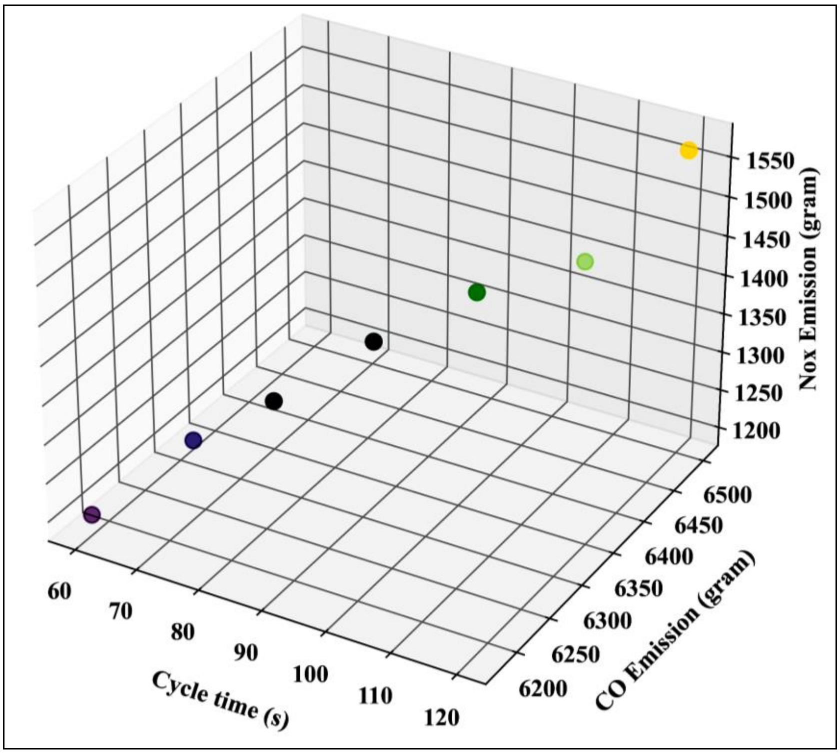

Fig 9: 3D Visualization of CO and NOx Emissions across Varying Signal Cycle Times.

4.4 Impact of Cycle Length on Fuel Consumption

Similar to emissions, the results regarding fuel consumption shown in Figure 10 had a similar trend. Different than emissions, maximum fuel consumption was at cycle time 120 seconds at a consumption of 93.02 US gallons of fuel while 60 seconds saw the minimum consumption of only 83.38 US gallons, resulting in a difference of 11.6%. This difference captures the impacts from periods of idling by engines, added stop time, and decreased performance when cycle times oscillate at the prime cycles. As in the results related to emissions, the general finding is that under constant operating demand conditions, shorter signal cycles will yield better fuel economy than longer cycles at urban signalized intersection conditions.

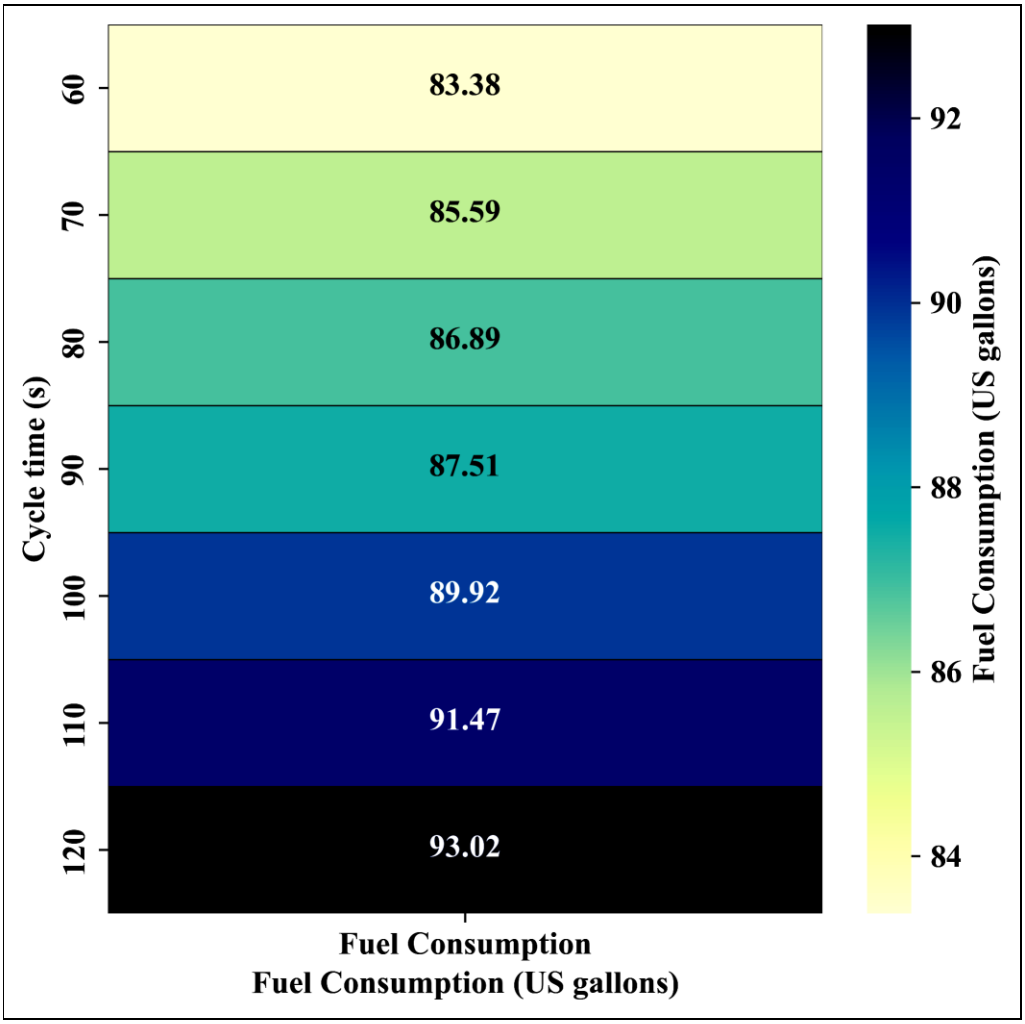

Fig 10: Average Fuel Consumption for Different Signal Cycle Durations.

4. Discussion

The findings of the study highlight a significant and statistically significant pattern with shorter signal cycle lengths (60-90 seconds) resulting in a meaningful increase in both traffic and environmental performance when compared to longer cycle lengths (110-120 seconds) at the four-leg intersection in Al-Qadisyah, Kirkuk. This utility was shown in the average queue length, vehicle delay, fuel consumption, and emissions of CO and NOx with shorter signal cycle lengths. The discrepancy can be attributed to the unique operational performance of signal timing - lower cycle lengths will reduce each driver's wait time at the red light and give vehicles more frequent opportunities to move through the intersection. This whole, of course, meant less vehicle queuing at the stop lines and resulted in less overall delay on all approaches through the intersection.

When considering the scientific ramifications of shorter signal cycles, fewer stop cycles would ensue; thus, reducing the duration which vehicles become dormant and the number of episodes of total stop-and-go experienced by vehicles, both of which are substantial contributors to congestion and vehicular emissions. Longer green durations can be attained through longer cycle lengths, but they generate longer red durations for other movements, which increases spillback and reduces throughput—as one would expect in a heavily urbanized and saturated context. These results are consistent with Calle-Laguna [29], who simulated microscopic conditions using the Integration model and demonstrated that conventional frameworks for estimating cycle lengths frequently yield longer-than-optimal cycle times which increases delay and fuel consumption. The authors established in their study of delays and emissions during heavy vehicle movements that superior conditions could be achieved by adapting to shorter cycle lengths along with their context.

The environmental indicators considered in this handle also support a shorter cycle period. When comparing the 60 second cycle to the 120 second cycle, CO emissions increased 5% and NOx emissions increased over 30%. This happened due to longer periods of engine idling and less efficient acceleration, both due to longer signal delays. This observation was mentioned earlier by Cohen and Euler [30], who said that signal cycles designed for the least delay are normally the same cycles that also have the lowest emissions and fuel use.

Furthermore, Lin *et al.* [31] determined that there exists a coordinated potential for the simultaneous reductions in vehicle delay and pollutants emitted, when signal timing is adjust in favor of minimizing excessive idling and start-stop conditions that are magnified by long rigid signal plans. Their trajectory analysis using VISSIM reinforces these findings, as shorter cycles led to smoother flow and reductions in harmful emissions. Moreover, case studies in developing contexts confirm these results. For example, Kareem and Alkaissi [32] determined that by reducing a long cycle of 240 seconds to in excess of 77% at a signalized intersection in Baghdad improved average vehicle delay and level of service, further confirming the benefits of shorter cycle times in similar developing urban traffic environments.

In summary, this study's findings corroborate a growing body of literature demonstrating that signal timing strategies that support moderate-to-short cycle lengths can enhance traffic operational performance and provide additional environmental benefits. However, those environmental benefits are only associated with a reasonable balance between service frequency and approaching extremely short cycle lengths may lead to less-than-ideal operational performance under heavily congested conditions or coordinated networks. This study does not consider those conditions, but for isolated intersections with regular approaches. As the study did, the reduction of cycle length is the most practical consideration to improve operational and ecological performance. The results provide insight into possible improvements to more effectively support traffic engineers and urban planners in efforts to enhance performance and sustainability of control plans at intersections in urban areas, including Kirkuk.

5. Conclusion

This study analyzed the effect of changing signal cycle length on traffic operation and sustainability at a four-leg signalized intersection in Al-Qadisyah, Kirkuk, Iraq. Using the PTV VISSIM microscopic simulation model, a stage-based signal controller with signal cycle lengths being tested ranged from 60 to 120 seconds (in 10 second increments). The study found that shorter signal cycle lengths, and particularly the 60 to 90 second signal cycle lengths produced a significant difference in average queue length, vehicle delay, CO and NOx emissions, and vehicle fuel consumption. The 60 second optimized signal cycle length produced vehicle queue length reductions up to 19.8% (21.9% delay cost), fuel reductions up to 10.4%, and reductions to NOx emissions up to 30.2% compared to an existing signal cycle length of 120 seconds democratically.

The results evidence that the effective implementation of the signal cycle length is a measurable treatment that will positively influence intersection efficiency and minimize negative externalities of urban travel behavior. Likewise, more context-sensitive reduced cycle lengths can assist with roadway congestion and health improvements associated with reduced exposures to pollutants in urban environments.

For further research, it would be valuable to broaden the scope to:

- Corridor-level optimization, where combining signal timings may be a different trade-off than isolated intersections post optimization.
- Adaptive signal control systems that can change cycle lengths based on real time traffic conditions.
- Mixed traffic conditions contain a heterogeneous fleet of vehicles (e.g., heavy goods vehicles, public transport, electric vehicles).
- Field validation, to compare simulation results to real world conditions for traffic and emissions performance results.
- Connected vehicle and autonomous vehicle integrations to learn how new technologies may work with optimized signal control.

Overall, this establishes evidence to continue supporting short and adaptive signal cycles, providing useful applications for traffic engineers and urban planners in evolving and developing cities (e.g., Kirkuk).

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