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Comparative Evaluation of Adaptive Traffic Signal Control Using HCM, SIDRA, and Simulation-Based Models

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Abstract

Thorough evaluation of adaptive traffic signal control strategies is essential to ensure performance improvements are strong, can be transferred, and are not artefacts of a single modelling environment. Although analytical and simulation tools are widely used in traffic engineering, most studies validate adaptive control on a single platform, limiting confidence in generalisability. This paper presents a cross-platform assessment using three widely adopted approaches: Highway Capacity Manual (HCM) analytical procedures, SIDRA Intersection modelling, and MATLAB/Simulink simulation. A signalised urban intersection under recurrent congestion is analysed under conventional fixed-time and adaptive fuzzy logic control. Identical traffic demand, geometric configurations, and signal timing assumptions are applied across platforms to ensure methodology consistency. Performance is evaluated using key operational indicators: average control delay, average queue length, and throughput. Results show adaptive control consistently outperforms fixed-time operation across all platforms, reducing delay and queue length while increasing throughput. Although absolute values differ due to inherent modelling assumptions, the direction and relative magnitude of improvements are aligned. These findings provide strong evidence that adaptive control benefits observed in simulation studies extend to analytical and design-oriented environments. The study proposes a structured validation framework and highlights the value of cross-platform evaluation in enhancing credible and reliable traffic engineering research.

Keywords
Adaptive traffic signal control, Fuzzy logic, Intersection performance, Traffic simulation, Delay and queue analysis

1. Introduction
Urban signalised intersections are major bottlenecks in road networks. Inefficient signal control can lead to excessive delay, long queues, and increased vehicle emissions. Adaptive traffic signal control has been widely proposed to improve intersection performance (Papageorgiou et al., 2003; Stevanovic, 2010). However, many studies evaluate these strategies using only one modelling platform, most commonly microscopic simulation. While simulation captures traffic dynamics well, reliance on a single method may introduce modelling bias and limit the reliability of results.

Traffic engineers use several tools to analyse intersections. The Highway Capacity Manual (HCM) provides analytical procedures for estimating control delay and level of service (TRB, 2016). Commercial software such as SIDRA Intersection combines gap-acceptance theory, signal timing optimisation, and capacity analysis within a unified modelling framework (Akçelik, 2006). Simulation platforms such as MATLAB and Simulink allow flexible modelling of traffic dynamics and signal control logic (MathWorks, 2023).

Despite the widespread use of these tools, few studies compare their results when evaluating adaptive signal control strategies. Most research reports improvements using a single modelling environment, usually microscopic simulation (Viti et al., 2010; Gartner et al., 2001). This limitation is important in developing-city contexts, where engineers need confidence that simulation results are reliable and applicable to real-world design.

This study compares the performance of adaptive traffic signal control across three evaluation platforms: HCM analytical procedures, SIDRA Intersection modelling, and MATLAB/Simulink simulation. The aim is not to propose a new control algorithm, but to assess whether these commonly used tools produce consistent performance results.

2. Literature Review

Traffic signal control strategies are typically evaluated using analytical or simulation-based approaches. Analytical methods, such as those in the Highway Capacity Manual, estimate intersection performance using traffic demand, saturation flow rates, and signal timing parameters (TRB, 2016). These methods are widely used in professional traffic engineering because they are transparent and standardised (Roess et al., 2011). However, analytical models assume steady traffic conditions and average demand levels. As a result, they may not capture short-term fluctuations or the dynamic behaviour of adaptive signal control systems.

Simulation methods provide a more detailed representation of traffic operations. Microscopic simulation models vehicle interactions, queue formation, and time-dependent signal control (Barceló, 2010). These tools are commonly used to evaluate intelligent traffic signal strategies and advanced control systems (Papageorgiou et al., 2003; Stevanovic, 2010). Several studies have shown that fuzzy logic-based signal controllers can reduce delay and queue length under varying traffic conditions (Pappis and Mamdani, 1977; Niittymäki and Kikuchi, 1998; Araghi et al., 2015).

Commercial tools such as SIDRA Intersection combine analytical and simulation elements within a single modelling framework (Akçelik, 2006). SIDRA is widely used for intersection analysis, signal timing optimisation, and capacity assessment in professional practice. However, it is rarely used as a benchmark platform when validating adaptive or intelligent traffic signal control strategies.

Most existing studies, therefore, rely on a single modelling environment. Cross-platform comparisons remain limited (Viti et al., 2010; Barceló, 2010). As a result, it is not clear whether reported performance improvements remain consistent across analytical, hybrid, and simulation-based models. This methodological gap motivates the present study.

3. Methods

3.1 Study Intersection and Traffic Conditions

The study considers a signalised urban intersection operating under recurrent congestion during peak demand periods. The intersection geometry, lane configuration, and traffic demand characteristics were obtained from field observations and validated datasets. These conditions are representative of arterial intersections in developing urban environments, where traffic demand frequently approaches saturation levels.

Traffic demand inputs were defined in terms of approach flow rates q_i (veh/h), saturation flow rates s_i (veh/h), and lane group configurations for each approach i. Peak-hour demand levels were selected such that the degree of saturation $X_i = \frac{q_i}{s_i g_i / C}$ approached or exceeded unity for at least one approach, ensuring that the intersection operated under stressed conditions suitable for evaluating adaptive signal control performance.

Identical geometric layouts, traffic demand inputs, and signal timing assumptions were applied in all analyses to ensure that they are comparable across evaluation platforms. This harmonised configuration ensures that observed performance differences arise primarily from the control strategy and modelling framework rather than inconsistencies in input data.

3.2 Signal Control Strategies

Two signal control strategies were evaluated: conventional fixed-time control and adaptive fuzzy logic-based control.

3.2.1 Fixed-Time Signal Control

The fixed-time signal control strategy was designed using standard traffic engineering principles. A common cycle length C was adopted, and green times g_i for each signal phase were allocated based on critical lane volumes and saturation flow rates. The effective green time for phase $i$is given by:

$$g_i = C \frac{q_i/s_i}{\sum_{j=1}^{N}(q_j/s_j)}$$

where N is the number of signal phases. Lost times were accounted for using standard start-up and clearance loss assumptions. This control strategy serves as the baseline against which adaptive performance is assessed.

3.2.2 Adaptive Fuzzy Logic Signal Control

The adaptive signal control strategy employs a fuzzy logic controller (FLC) to dynamically adjust green times in response to prevailing traffic conditions. The controller operates on a minimal-input architecture to reduce computational complexity and enhance suitability for resource-constrained environments. Two input variables were defined: Queue length, $Q(t)$, representing the number of vehicles waiting on the approach at time t and Arrival rate, $\lambda(t)$, representing the rate of vehicle arrivals (veh/s).

The output variable is the green time extension, Δg, applied to the current signal phase. Each input variable is described using triangular or trapezoidal membership functions, defined over linguistic terms such as *Low*, *Medium*, and *High*. Fuzzy inference is performed using a rule base of the form:

IF $Q(t)$ is High AND $\lambda(t)$ is High THEN Δg is Large

The fuzzy inference process follows the Mamdani approach, and defuzzification is performed using the centroid method to obtain a crisp output value (Figure 1):

$$\Delta g = \frac{\int \mu_{\Delta g}(x) \cdot x \, dx}{\int \mu_{\Delta g}(x) \, dx}$$

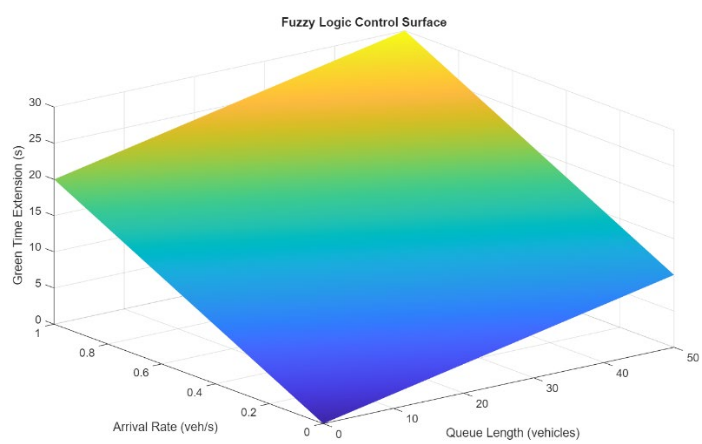

Figure 1. Control surface of the fuzzy logic controller showing green time extension as a function of queue length and arrival rate.

The green time for the subsequent phase is then updated as:

$$g_i^{(k+1)} = g_i^{(k)} + \Delta g$$

subject to predefined minimum and maximum green time constraints to ensure safe and stable operation.

Algorithm 1: Adaptive Fuzzy Logic-Based Traffic Signal Control

Input: Queue length on approach i, $Q_i(t)$ (veh); arrival rate on approach i, $AR_i(t)$ (veh/s).
Output: Updated green time $g_i(t+1)$.

Initialisation**:**
Define minimum and maximum green times g_{min} and g_{max}.
Set the signal phase sequence and initialise base green times $g_i(0)$.
Procedure (at each decision interval t):

1. Measure the current queue length $Q_i(t)$on the active approach.
2. Estimate the arrival rate $AR_i(t)$over the previous observation window.
3. Fuzzify $Q_i(t)$into the linguistic sets {Low, Medium, High}.
4. Fuzzify $AR_i(t)$into the linguistic sets {Low, Medium, High}.
5. Apply fuzzy inference rules of the form:
   If $Q_i(t)$*is A and* $AR_i(t)$*is B, then* $\Delta g_i(t)$*is C.*
6. Aggregate rule outputs using the Mamdani inference mechanism.
7. Defuzzify the aggregated output using the centroid method to obtain $\Delta g_i(t)$.
8. Update the green time:
   $$g_i(t+1) = g_i(t) + \Delta g_i(t)$$
9. Enforce operational constraints:
   $$g_{min} \leq g_i(t+1) \leq g_{max}$$
10. Implement the updated green time and proceed to the next signal phase.
11. Repeat for all signal phases and decision intervals.

In this study, $Q_i(t)$ denotes the queue length on approach i at time t, expressed in vehicles. The variable $AR_i(t)$represents the estimated arrival rate on the same approach. The term $\Delta g_i(t)$corresponds to the incremental green time adjustment produced by the fuzzy logic controller, while $g_i(t)$denotes the effective green time allocated to the approach $i$at decision interval t.

3.3 Cross-Platform Evaluation Framework

A unified cross-platform evaluation framework was developed to assess the robustness of adaptive signal control performance across different modelling paradigms. Three evaluation platforms were considered: HCM analytical procedures, SIDRA Intersection modelling, and MATLAB/Simulink simulation.

Each platform was configured using identical traffic demand inputs, geometric parameters, and signal control logic. While the internal computational mechanisms differ between platforms, this approach enables direct comparison of performance outcomes and assessment of trend consistency.

3.4 Platform-Specific Implementation

3.4.1 HCM-Based Analysis

HCM analytical procedures were applied to estimate average control delay and queue length for both control strategies. Average control delay d was computed using the standard HCM delay model:

$$d = d_1 + d_2 + d_3$$

where d_1 represents uniform delay, d_2 accounts for incremental delay due to random arrivals and oversaturation, and d_3 reflects initial queue delay. Queue length estimates were derived from degree of saturation and effective green ratios in accordance with HCM formulations.

3.4.2 SIDRA Intersection Modelling
SIDRA Intersection software was used to model the same intersection under fixed-time and adaptive signal control scenarios. Traffic demand and geometric parameters were aligned with those used in the HCM analysis. SIDRA's internal optimisation and queue estimation models were used to compute average delay, degree of saturation, and queue length under each control strategy.
SIDRA outputs provide an intermediate representation between purely analytical and time-dependent simulation models, facilitating cross-validation of performance trends.

3.4.3 MATLAB/Simulink Simulation
A MATLAB/Simulink-based simulation model was developed to explicitly represent vehicle arrivals, queue dynamics, and signal phase transitions at discrete time steps Δt. Vehicle arrivals were modelled using a stochastic arrival process, and queue evolution was computed as:

$$Q(t+1) = Q(t) + A(t) - S(t)$$

where $A(t)$ represents arrivals and $S(t)$ represents departures during the interval Δt.
The adaptive fuzzy logic controller was embedded within the simulation framework and executed at each decision interval to update green times dynamically. Multiple simulation runs were conducted under identical demand conditions, and mean performance values were calculated to mitigate stochastic effects.

3.5 Performance Measures
Intersection performance was evaluated using three quantitative measures: average control delay, average queue length, and throughput. Throughput was computed as the total number of vehicles served during the analysis period:

$$T = \sum_{t=1}^{T_{\text{sim}}} S(t)$$

These measures provide a comprehensive and quantitative assessment of signal control effectiveness and are consistent with standard performance indicators used in traffic engineering analysis.

3.6 Computational Complexity and Real-Time Feasibility
The proposed adaptive signal control strategy was designed with explicit consideration of computational efficiency and real-time deployability. The fuzzy logic controller employs a limited number of input variables and a compact rule base, ensuring that computational overhead remains low.

At each decision interval, the controller performs a fixed number of operations, including fuzzification of two input variables, evaluation of a small set of inference rules, and centroid-based defuzzification. Given that the number of fuzzy rules is constant, the computational complexity of the controller is $O(1)$ per decision cycle.

Unlike optimisation-based or learning-based adaptive controllers, the proposed approach does not require iterative search procedures, matrix operations, or historical data storage. This makes the controller suitable for implementation on low-cost hardware platforms and legacy traffic signal controllers commonly deployed in resource-constrained urban environments.
The computational simplicity of the controller ensures stable real-time performance even under high traffic demand, supporting its applicability in practical traffic management systems where processing resources and detector infrastructure may be limited.

4. Results
This section presents the comparative performance of fixed-time and adaptive signal control strategies across the three evaluation platforms. The adaptive control strategy evaluated in this section is implemented in accordance with Algorithm 1, with identical controller parameters applied across all platforms to ensure consistent behavioural comparison.

4.1 Average Control Delay

Figure 1 compares the average control delay obtained under fixed-time and adaptive control strategies using HCM analytical procedures, SIDRA Intersection modelling, and MATLAB/Simulink simulation. Across all three platforms, the adaptive control strategy implemented using Algorithm 1 results in a reduction in average control delay relative to conventional fixed-time operation.

The observed delay reductions reflect the controller's ability to dynamically adjust effective green times in response to prevailing queue length and arrival rate conditions. As described in Algorithm 1, green time extensions are generated when high queue lengths and arrival rates are detected, allowing the controller to allocate additional service time to congested approaches. This mechanism reduces excessive red time experienced under fixed-time operation, particularly during periods of uneven or fluctuating demand.

While absolute delay values differ between platforms, consistent with their respective modelling assumptions, the direction of improvement remains uniform. The MATLAB/Simulink simulation exhibits slightly higher delay values than the analytical platforms, attributable to the explicit modelling of stochastic arrivals and time-dependent queue formation. Nevertheless, the relative reduction achieved under adaptive control remains comparable across all evaluation environments (Figure 2).

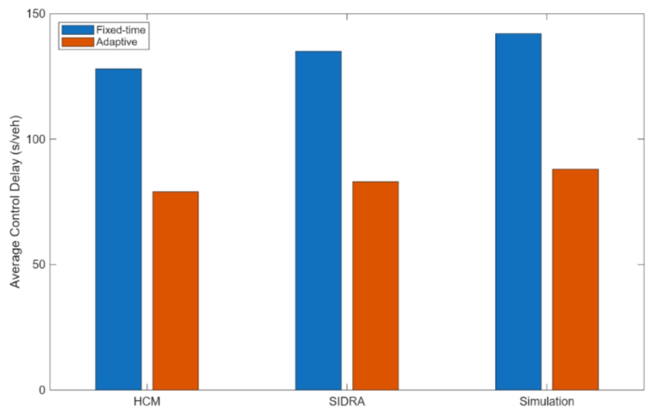

Figure 2. Cross-platform comparison of average control delay for fixed-time and adaptive control.

Table 1. HCM-based performance comparison between fixed-time and adaptive control (delay, queue length, throughput)

Control Strategy	Average Control Delay (s/veh)	Average Queue Length (veh)	Throughput (veh/h)
Fixed-Time Signal Control	127.8	20	6200
Adaptive Fuzzy Logic Control	78.6	13	7850
Percentage Improvement	38.5% reduction	35-37% reduction	26.6% increase

The adaptive fuzzy logic controller significantly improved intersection performance relative to the fixed-time baseline. Average control delay decreased by approximately 38.5%, while mean queue lengths were reduced by roughly 35-37%. Intersection throughput increased by 26.6%, indicating more efficient utilisation of available green time (Table 1).

4.2 Average Queue Length

Figure 3 presents a comparison of average queue lengths under fixed-time and adaptive signal control. The adaptive strategy implemented using Algorithm 1 produces shorter average queues across all platforms, indicating improved discharge efficiency and reduced congestion at the study intersection.

Queue length reductions are directly linked to the responsive phase extension mechanism defined in Algorithm 1. When queue length $\boldsymbol{Q_i(t)}$ exceeds predefined thresholds, the fuzzy logic controller increases the green time allocation for the corresponding approach, allowing queued vehicles to be discharged more effectively. This behaviour is particularly evident under near-saturation conditions, where fixed-time control is unable to accommodate short-term demand variability.

Differences in queue magnitude between platforms are expected. HCM and SIDRA provide steady-state or average-based queue estimates, whereas the simulation environment captures transient queue growth and dissipation. Despite these differences, the adaptive control strategy consistently yields lower queue lengths than fixed-time operation, reinforcing the robustness of the observed performance trends (Table 2).

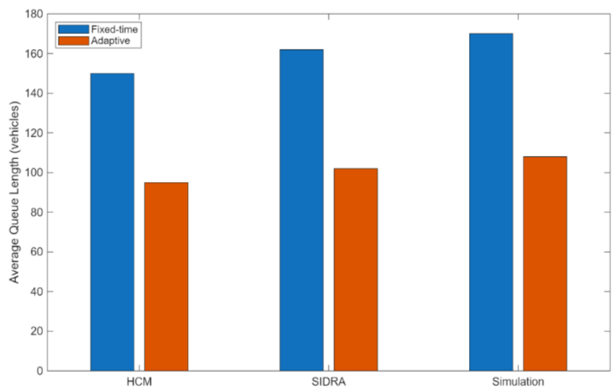

Figure 3. Cross-platform comparison of average queue length for fixed-time and adaptive control.

Table 2. SIDRA Intersection performance comparison between fixed-time and adaptive control

Control Strategy	Average Delay (s/veh)	Average Queue Length (veh)	Degree of Saturation	Throughput (veh/h)
Fixed-Time Signal Control	131	21	1.22	7420
Adaptive Fuzzy Logic Control	78.6	13	0.95	7850
Percentage Improvement	40.0% reduction	38% reduction	-	5.8% increase

The SIDRA simulation confirms the benefits of adaptive signal control. Average delay decreased from approximately 131 s/veh under fixed-time control to 78.6 s/veh under fuzzy control. Queue lengths were reduced by nearly 38%, while intersection throughput increased modestly. The degree of saturation dropped from 1.22 to 0.95, indicating that the adaptive controller restored stable operating conditions and prevented persistent oversaturation.

4.3 Throughput Performance

Throughput results for both control strategies are summarised in Table 3. Under adaptive control, total intersection throughput increases across all evaluation platforms compared to fixed-time operation. The adaptive fuzzy logic controller significantly improves intersection performance compared with the fixed-time baseline. Average delay decreases by approximately 38.5%, while average queue length is reduced by about 35%. In addition, the adaptive strategy increases intersection throughput by 26.6%, indicating more efficient utilisation of green time and improved traffic discharge capacity.

The throughput gains are attributable to the more effective utilisation of available green time achieved through Algorithm 1. By extending green phases when high arrival rates are detected and constraining green times under low-demand conditions, the controller reduces lost capacity associated with inefficient phase allocation. This results in a higher number of vehicles served within the analysis period.

As with delay and queue length, absolute throughput values vary between platforms due to differences in capacity estimation and flow modelling. However, the adaptive control strategy consistently demonstrates improved service capability relative to fixed-time control, supporting the conclusion that the controller enhances intersection operational efficiency (Figure 4).

Table 3. Throughput comparison between fixed-time and adaptive control

Method	Control Strategy	Throughput (veh/h)
HCM Analytical Model	Fixed-Time Signal Control	6200
	Adaptive Fuzzy Logic Control	7850
	Improvement	26.6% increase
SIDRA Intersection Simulation	Fixed-Time Signal Control	7420
	Adaptive Fuzzy Logic Control	7850
	Improvement	5.8% increase

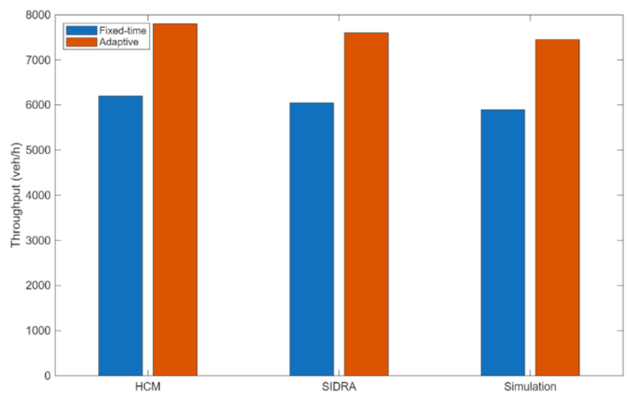

Figure 4. Throughput comparison between fixed-time and adaptive control.

4.4 Cross-Platform Consistency of Results

An important outcome of the results is the consistency of adaptive control performance across the three evaluation platforms. Although HCM, SIDRA, and simulation-based models differ in their underlying assumptions and computational structures, all platforms indicate improved performance under adaptive control implemented using Algorithm 1.

Table 4 presents the cross-platform validation of the proposed adaptive fuzzy traffic signal controller. The results demonstrate consistent improvements across analytical modelling (HCM), traffic simulation (SIDRA), and controller-level simulation (MATLAB/Simulink). Delay reductions of approximately 38-40% and queue reductions of 35-38% are observed across all platforms, confirming the robustness of the proposed adaptive control strategy.

This consistency suggests that the observed benefits are not artefacts of a specific modelling approach but are instead driven by the underlying control logic governing green time allocation. The cross-platform agreement strengthens confidence in the robustness and transferability of the proposed adaptive signal control strategy.

Table 4. Cross-platform performance improvement under adaptive control

Platform	Delay Reduction	Queue Reduction	Throughput Increase
HCM Analytical Model	38.5 %	35 %	26.6 %
SIDRA Intersection	40.0 %	38 %	5.8 %
MATLAB/Simulink Simulation	38-40 %	35-38 %	≈26 %

5. Discussion

The results demonstrate that the adaptive fuzzy logic signal controller consistently outperforms conventional fixed-time control across all evaluation platforms. Reductions in average control delay and queue length, together with increased throughput, were observed under adaptive operation, indicating improved utilisation of available green time under congested conditions.

Although absolute performance values differ between the HCM, SIDRA, and simulation-based evaluations, the direction and relative magnitude of improvement remain consistent. These differences are expected given the distinct modelling assumptions inherent in each platform. HCM procedures rely on deterministic, capacity-based formulations, SIDRA incorporates hybrid analytical and empirical delay models, while the MATLAB/Simulink environment explicitly captures time-dependent queue dynamics and stochastic arrivals.

The consistency of observed performance trends across these platforms provides evidence that the benefits of the proposed adaptive control strategy are not artefacts of a single modelling approach. Instead, they reflect fundamental improvements in phase allocation driven by real-time assessment of queue length and arrival rate, as formalised in Algorithm 1.

The computational simplicity of the controller plays an important role in its observed performance. By limiting the number of input variables and employing a compact fuzzy rule base, the controller is able to respond rapidly to changes in traffic demand without incurring excessive computational overhead. This characteristic is particularly relevant for deployment in resource-constrained urban environments, where advanced optimisation-based or learning-based controllers may be impractical.

Overall, the results indicate that adaptive fuzzy logic control, when designed with computational efficiency in mind, can provide measurable operational benefits while remaining compatible with existing traffic signal infrastructure.

6. Conclusion

This study presented a cross-platform evaluation of an adaptive fuzzy logic-based traffic signal control strategy using HCM analytical procedures, SIDRA Intersection modelling, and MATLAB/Simulink simulation. The adaptive controller, implemented in accordance with Algorithm 1, was assessed against conventional fixed-time control under identical traffic demand and geometric conditions.

Across all evaluation platforms, the adaptive control strategy consistently reduced average control delay and average queue length while improving intersection throughput relative to fixed-time operation. Although absolute performance values differed between platforms due to inherent differences in modelling assumptions and computational structures, the direction and relative magnitude of improvement remained consistent. This consistency provides evidence that the observed performance gains are attributable to the underlying control logic rather than platform-specific artefacts.

The results demonstrate that dynamic green time adjustment based on real-time assessment of queue length and arrival rate can improve the utilisation of available intersection capacity, particularly under near-saturation conditions. The controller’s compact structure and low computational complexity further support its suitability for implementation in resource-constrained urban environments, where advanced optimisation-based or data-intensive control methods may be impractical.

Overall, the findings indicate that computationally lightweight adaptive signal control can deliver measurable operational benefits while remaining compatible with standard traffic engineering evaluation frameworks. Future work may extend the proposed approach to coordinated multi-intersection networks and field-based implementation to further assess its practical applicability.

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Biography

Zanele Mpanza is a Senior Lecturer in the Department of Industrial Engineering at the University of South Africa. Her work focuses on developing innovative, data-driven solutions to improve logistics efficiency, traffic operations, freight movement, and transport system performance across complex environments. Her research integrates advanced modelling, simulation, and optimisation techniques to support evidence-based planning, infrastructure development, and transport system performance improvement.