1. Objective

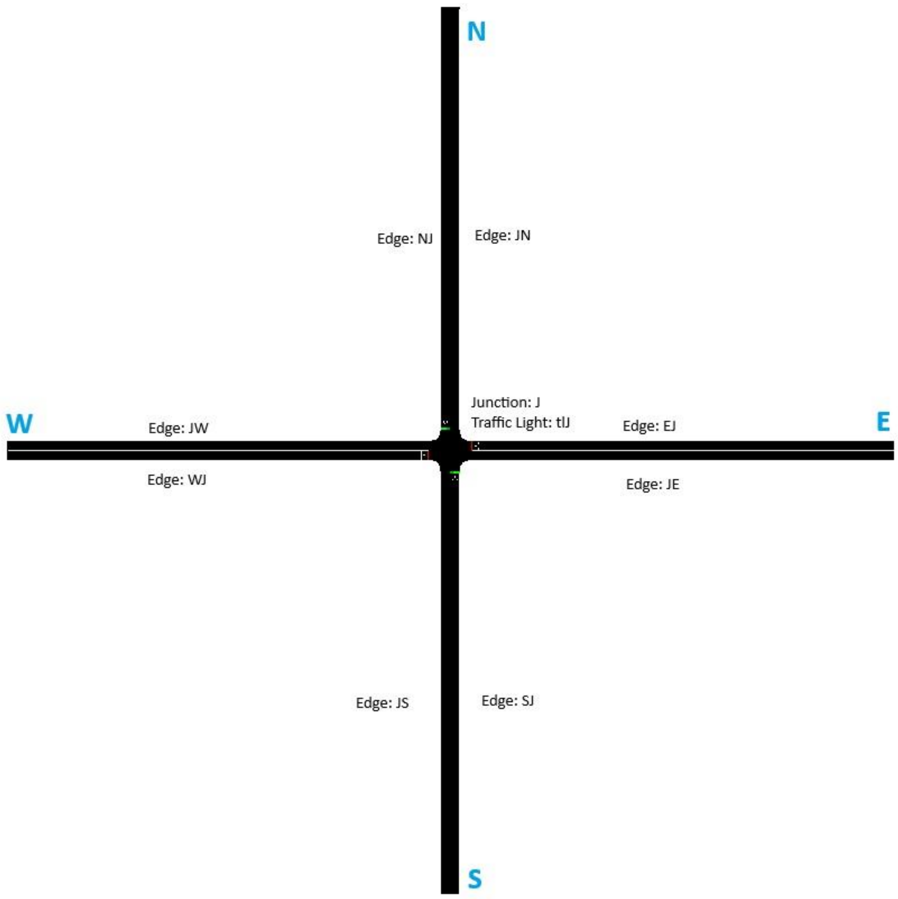
To evaluate various traffic scenarios in controlled simulation using SUMO and TraCI, focusing on a single intersection. These experiments aim to verify metric collection, observe basic traffic behaviour, and prepare for reinforcement learning-based optimisation in future work.

2. Simulation Setup

SUMO and Python files for the various experiments are available in GitHub at: https://github.com/PieterseFrancois/rl-traffic-light-optimisation

2.1 Network Design

The simulation environment consists of a single, four-way intersection designed to isolate and observe traffic flow behaviour under controlled conditions. The intersection uses a basic lane layout, with each approach featuring a single lane of 150 metres in each direction and the default traffic light configurations as provided by SUMO. A visual representation of the intersection layout is provided in the diagram below to give context to the network used in all experiments.



2.2 Metrics Tracked

The following metrics were tracked in the experiments grouped by the cardinal directions as indicated on the intersection diagram:

- Average waiting time per lane
- Queue length per lane
- Lane speed

3. Experiment Descriptions and Results

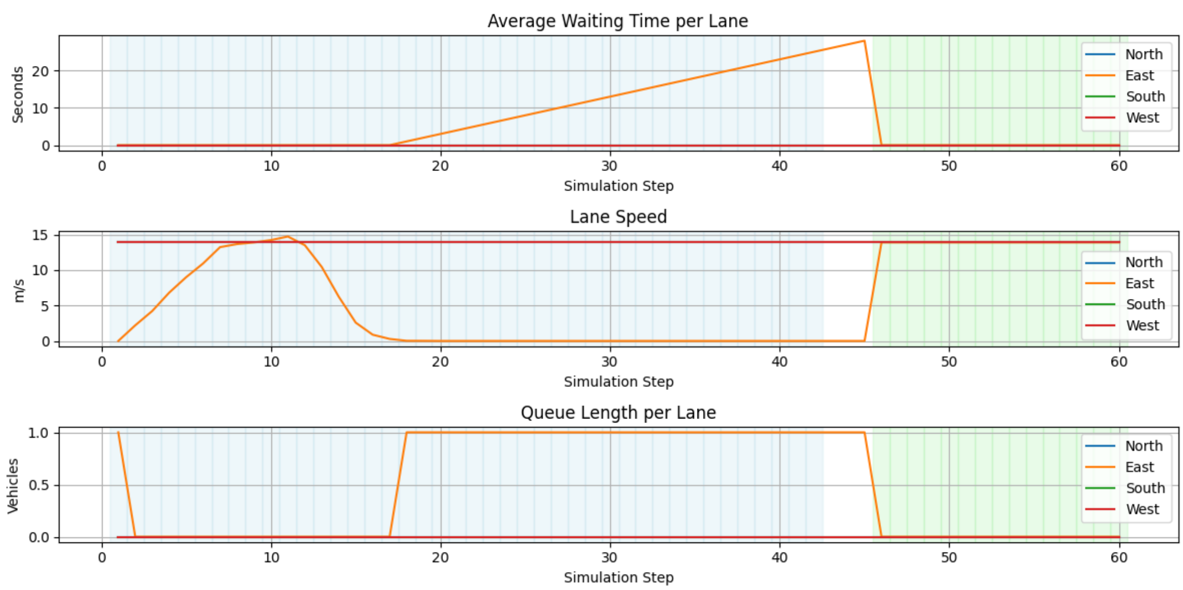
3.1 Single Vehicle Test

Purpose:
This experiment serves as a sanity check to verify that the simulation environment, traffic signal logic, routing, and metric collection are all functioning correctly. A single vehicle is introduced into the network to ensure it can pass through the intersection without interference or errors.

Setup:
One vehicle (veh0) is spawned at the start of the simulation and follows a simple east-to-west route across the intersection (EJ to JW). The default SUMO traffic light schedule is used, and the simulation tracks lane-specific metrics (waiting time, speed, queue length) on all four approaches using a custom metrics module. Data is collected at each simulation step via the TraCI interface.

Expected Results:
Given the simplicity of the setup and absence of other vehicles, the vehicle queue lengths should never exceed one. This confirms the correctness of the route definition, signal timing, and data collection pipelines.

Observation(s):
Shaded backgrounds indicate active green phases: blue for North–South and green for East–West traffic flow.



The vehicle stopped during the North–South green phase (blue), resulting in increased waiting time and zero speed. Once the East–West phase turned green (green region), it moved through the intersection, clearing the queue and restoring speed. The metrics confirm correct signal response and vehicle behaviour.

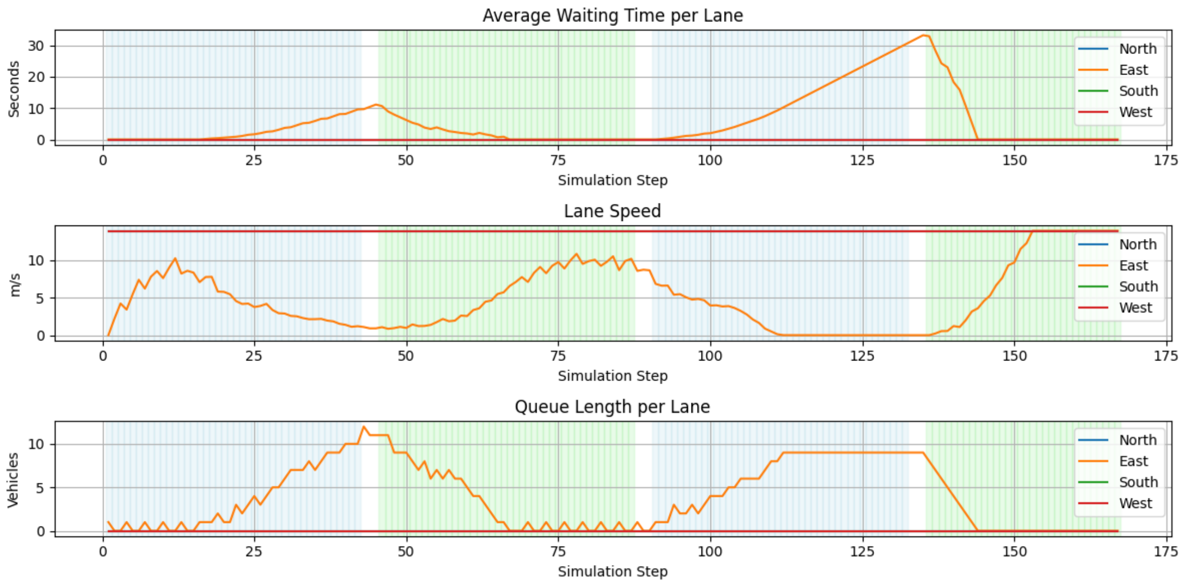
3.2 Single-Direction Vehicle Flow

Purpose:
This experiment establishes a baseline for traffic behaviour under light to moderate load in one direction. It is used to observe queue formation, waiting time trends, and phase response when a moderate volume of vehicles flows without cross-directional interference.

Setup:
Thirty vehicles were introduced from the east, travelling west through the intersection. Vehicles departed at one-second intervals on a shared route (EJ to JW). The network and traffic light remained unchanged from the previous experiment, and lane metrics were collected on all approaches.

Expected Results:
It is expected to observe minor queuing when the East–West signal is red (during the North–South green phase) and steady flow during the East–West green phase. Waiting time and queue lengths should rise and fall in sync with the signal phases, while lane speed should drop during red phases and rise again when vehicles are allowed to move.

Observation(s):
Shaded backgrounds indicate active green phases: blue for North–South and green for East–West traffic flow.



The vehicle flow builds up a queue during North–South green phases, reflected in the increasing waiting time and queue length between steps 0 and 40 and again after step ~80. Once the East–West phase becomes active, queues clear and speed rises sharply. This pattern repeats predictably, confirming that signal timing effectively regulates flow but causes a brief buildup during the red phase.

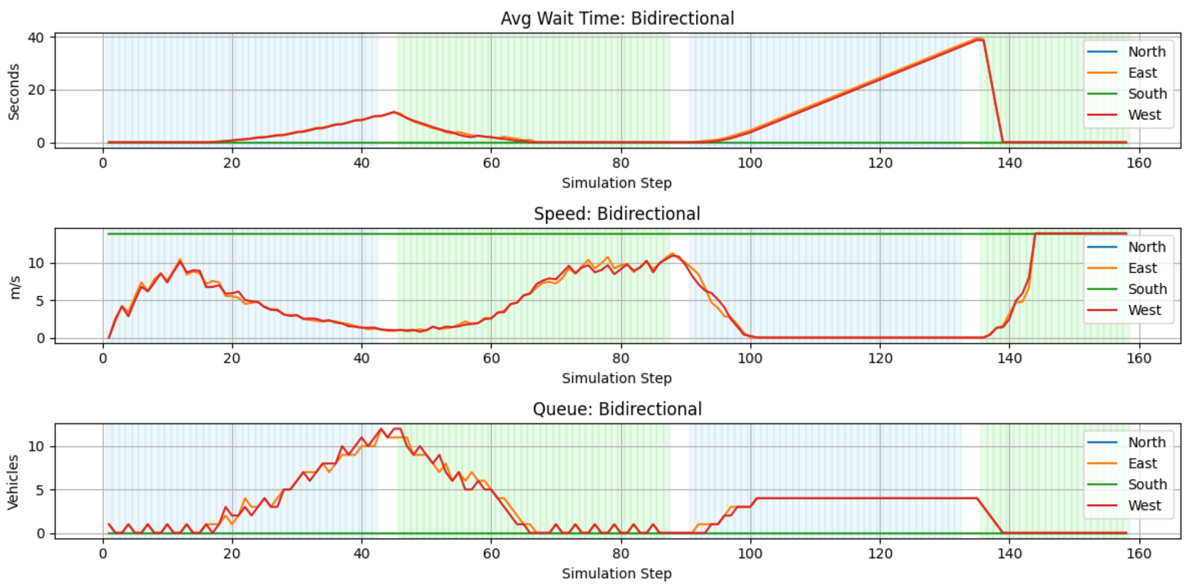
3.3 Bidirectional Balanced Flow

Purpose:
To evaluate the performance of the default traffic signal logic when managing balanced opposing flows. The focus is on fairness between directions, queue build-up and clearance timing, and whether signal phases serve both flows evenly. Furthermore, it validates the grouping of metric collection.

Setup:
Fifty vehicles were introduced in total, with 25 travelling east to west and 25 west to east. Vehicles were spawned at one-second intervals per direction, using separate but symmetric routes (EJ to JW and WJ to JE). The traffic light configuration and signal phases remained unchanged. Lane-specific metrics were recorded for all four approaches.

Expected Results:
If the signal phases are fair and symmetrical, average waiting times, speeds, and queue lengths should be similar for both directions.

Observation(s):
Shaded backgrounds indicate active green phases: blue for North–South and green for East–West traffic flow.



The metrics show similar patterns for both East and West lanes, with queue formation occurring during red phases and clearing when green. Speeds follow a periodic pattern aligned with the signal, confirming effective throughput. Waiting times and queue lengths remain the same across directions, indicating that the default signal plan handles bidirectional flow the same.

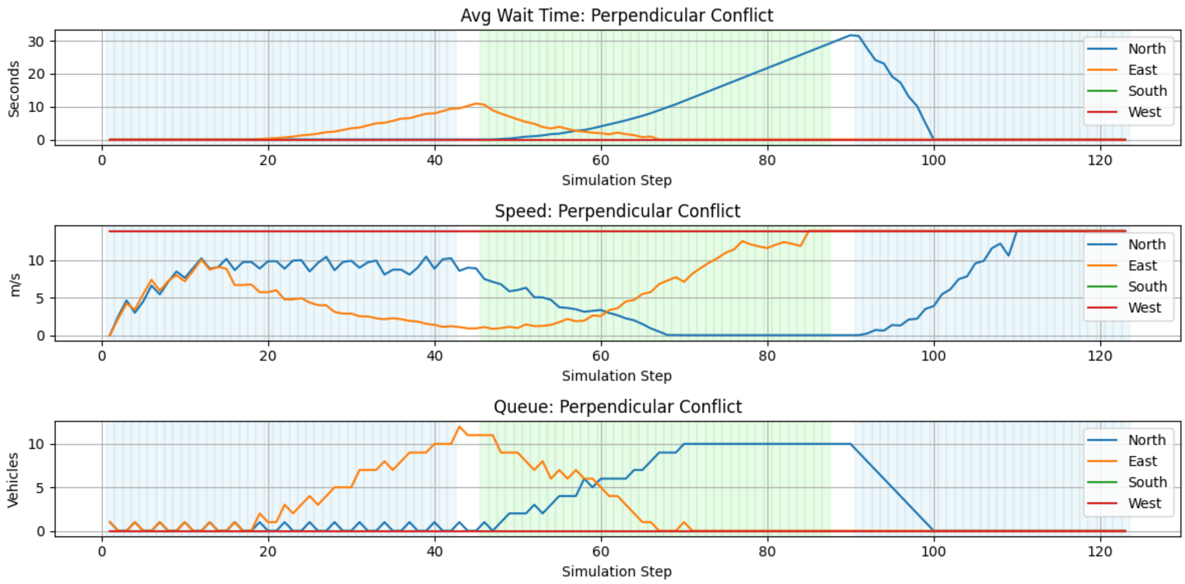
3.4 Perpendicular Flow with Conflict

Purpose:
To evaluate how the default traffic signal phases manage intersecting traffic flows of equal volume. The aim is to observe queue dynamics, waiting times, and phase fairness when two perpendicular directions compete for green time.

Setup:
A total of 40 vehicles were introduced, 20 travelling north to south and 20 travelling east to west. Vehicles departed at one-second intervals on their respective routes (NJ to JS and EJ to JW). The intersection signal logic remained unchanged, with green phases alternating between the two movement axes. Lane-specific metrics were recorded throughout.

Expected Results:
Alternating queue formation is expected as each direction is stopped during its red phase. Alternating clearance should then occur as green time shifts between the conflicting flows. Waiting times and speeds should display similar behaviour.

Observation(s):
Shaded backgrounds indicate active green phases: blue for North–South and green for East–West traffic flow.



The East lane exhibits rising wait times and queue length during the initial North–South green phase, which then clears during the first East–West phase. Subsequently, the North lane accumulates vehicles and waiting time while East–West traffic flows. Speeds drop to zero during red phases and recover during green.

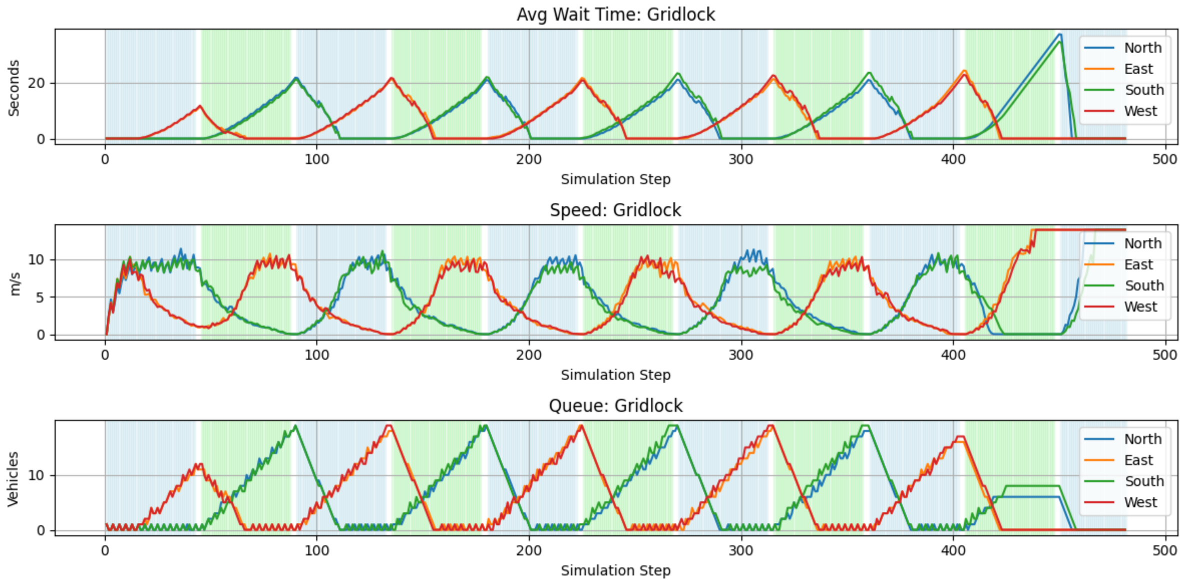
3.5 Gridlock Scenario

Purpose:
To test how the fixed-time traffic signals perform under very high traffic demand and to examine what happens when lane queue capacity is reached.

Setup:
A large number of vehicles (100 per direction) were added from all four approaches. Vehicles travelled straight through the intersection and departed at short intervals to create oversaturation. The intersection's 150 m lanes were expected to fill up during red phases, blocking movement during greens.

Expected Results:
As traffic builds up, queues should grow and become harder to clear between green phases. In a single-intersection setup, true gridlock does not occur because vehicles exit the simulation after crossing. However, the test helps show how quickly queues reach full capacity and whether movement is still possible once lanes are full.

Observation(s):
Shaded backgrounds indicate active green phases: blue for North–South and green for East–West traffic flow.



Queue build-up and clearance occur in regular cycles. The green phases are long enough to fully clear queues, even when lanes are saturated up to the 150 m limit. Based on the data, a full 150 m lane holds around 15 to 16 vehicles. As traffic demand continues, the system remains at high utilisation, with queues reaching full length before each green. While speeds drop during red phases, they recover reliably, and throughput is maintained — showing that the fixed-time phases can still handle maximum lane capacity, though with rising delays. This behaviour may change in a larger network where downstream congestion prevents clearing during green phases, leading to potential spillback and more severe breakdowns in flow.

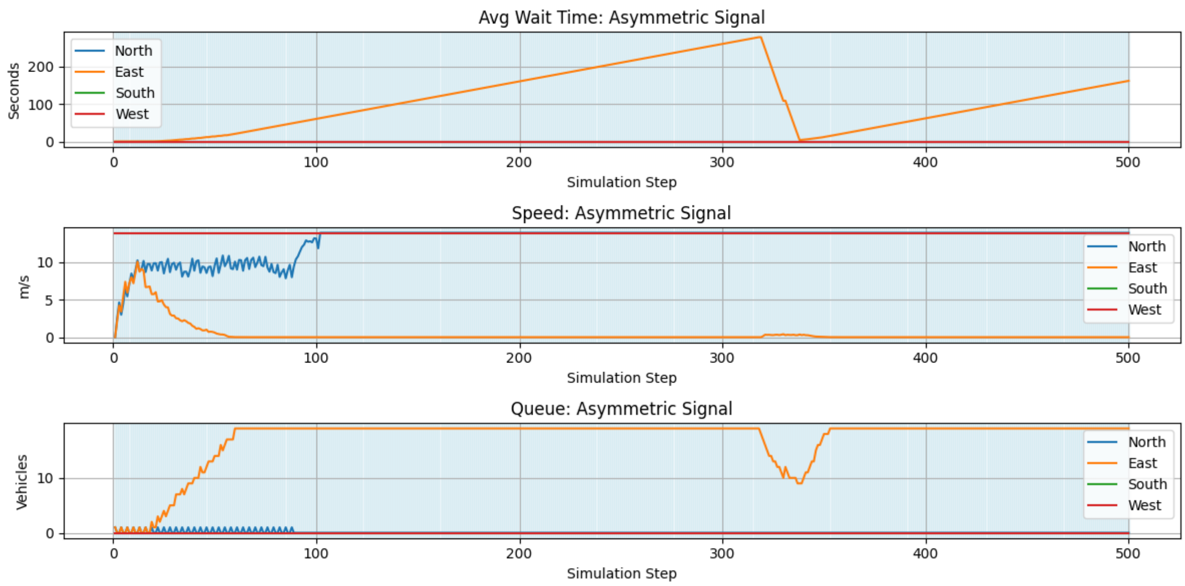
3.6 Asymmetric Signal Timing

Purpose:
To observe the effect of extreme signal imbalance by giving one direction continuous green time while keeping the perpendicular direction permanently red. The aim is to confirm whether saturation occurs and how it appears in the tracked metrics.

Setup:
Thirty vehicles were spawned on two routes: from North to South (NJ to JS) and from East to West (EJ to JW). A custom traffic light program was applied that kept North–South directions green and East–West directions permanently red. This created a fixed imbalance, favouring only one direction.

Expected Results:
The North–South flow should move without interruption. East–West traffic is expected to steadily increase until queue saturation is reached with a linearly growing average waiting time. Speeds should remain near zero.

Observation(s):
Shaded backgrounds indicate active green phases: blue for North–South and green for East–West traffic flow.



Results show continuous movement and stable speeds on the North approach, with minimal queuing. The East approach becomes saturated, with a full queue forming and average waiting time increasing steadily in a near-linear fashion. Around simulation step 330, a sharp drop in waiting time and queue length is observed. This is due to vehicles being automatically removed from the simulation after remaining stationary for 318 seconds. It is important to note this behaviour as it may become important in larger simulations. Before this vehicle despawning, the East approach followed the expected pattern of full queue saturation and delay accumulation under a permanently red signal.

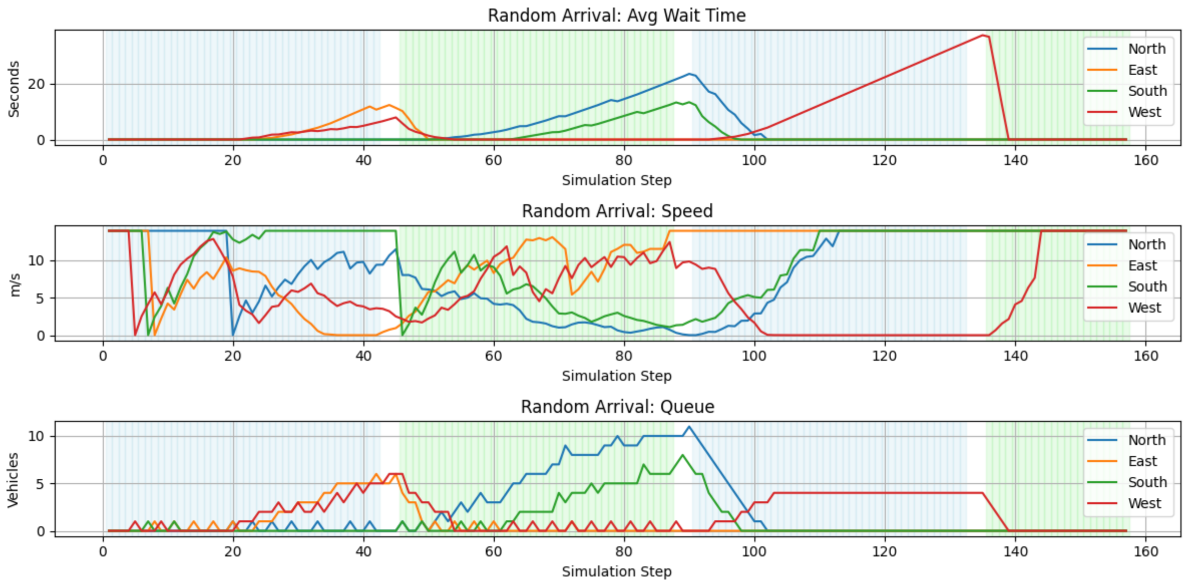
3.7 Random Vehicle Arrivals

Purpose:
To test the behaviour of fixed-time signal control under irregular and unpredictable traffic input. This setup mimics more realistic urban traffic conditions where vehicles arrive at non-uniform intervals from multiple directions.

Setup:
Sixty vehicles were generated with randomly selected routes from the following: North to South (NJ to JS), South to North (SJ to JN), East to West (EJ to JW), and West to East (WJ to JE). Each vehicle was assigned a random departure time between 0 and 90 seconds. For this simple experiment no defined literature based distributions were utilised. All other simulation parameters remained unchanged.

Expected Results:
Due to the random timing and route selection, queues and waiting times were expected to vary across directions and over time. Delays should appear temporarily in specific lanes depending on the signal phase.

Observation(s):
Shaded backgrounds indicate active green phases: blue for North–South and green for East–West traffic flow.



All directions show periods of queue build-up followed by clearance, reflecting the random arrival pattern and phase changes. Speeds remain variable and generally recover after each green phase. Waiting times grow in phases and then drop as vehicles are cleared. The results demonstrate how fixed signal control handles varying demand levels and show the importance of phase timing in mitigating unpredictable queues as observed by the large waiting time of the four vehicles in the region of 100 to 140 seconds.

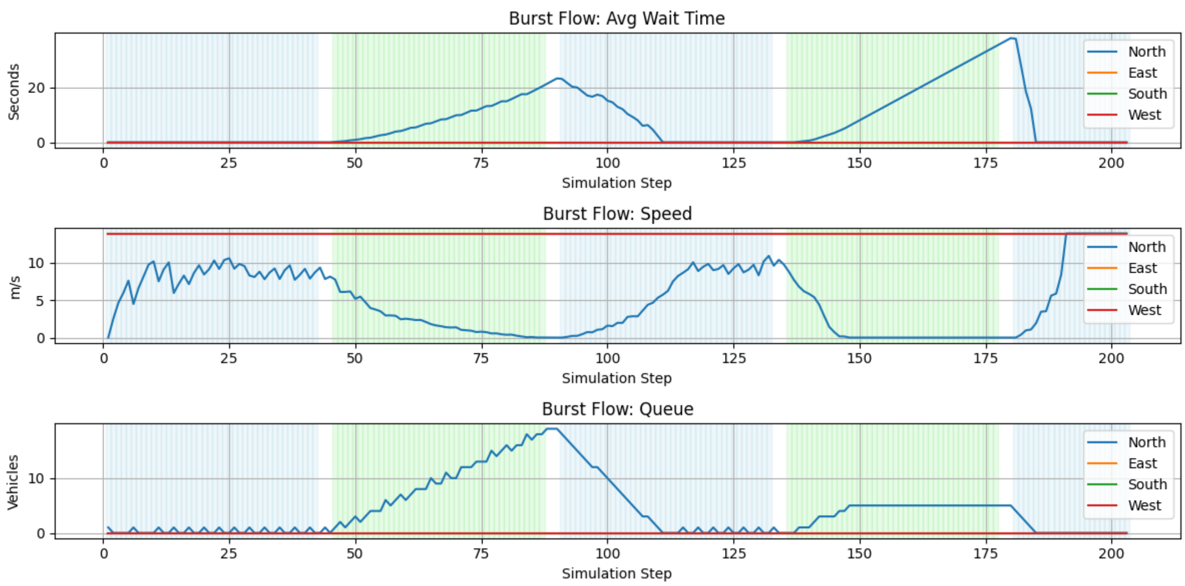
3.8 Burst Traffic Flow

Purpose:
To explore how fixed-time traffic signals respond to uneven vehicle arrivals by injecting bursts of traffic into an otherwise steady flow. The aim is to observe how queues form and recover around these sudden increases in demand.

Setup:
Vehicles were added from the North approach (NJ to JS). A steady base flow was maintained, with additional bursts of 10–15 vehicles injected at random intervals. Bursts occurred approximately every 10 seconds with a given probability, and burst vehicles departed in quick succession. Standard signal timing was used.

Expected Results:
Queues and delays were expected to rise sharply during burst events and gradually return to normal if green time was sufficient to clear the backlog before the next burst. Speed was expected to drop during burst build-up and recover once the queue cleared.

Observation(s):
Shaded backgrounds indicate active green phases: blue for North–South and green for East–West traffic flow.



The metrics show queue build-up and recovery consistent with changing inflow, but the intended burst pattern is not clearly distinguishable in the results. This is likely due to the short edge length and queue saturation limit of around 15 vehicles, which constrains how much of each burst is captured within the simulation area. As a result, queues are cleared relatively quickly, and the signal phase appears sufficient to recover before the next burst. This experiment may yield more meaningful insights in a larger or multi-intersection network where bursts can propagate, accumulate, and affect downstream flow more realistically.

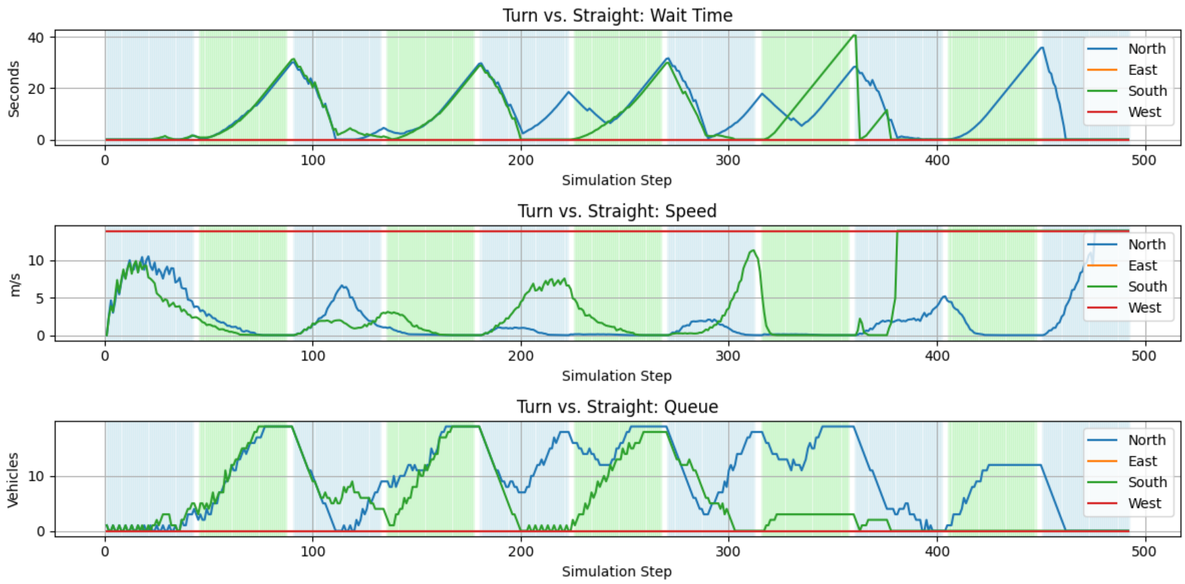
3.9 Turning vs. Straight Flow

Purpose:
To assess how mixed vehicle movements (straight, left, and right) from the same approach affect overall flow, queuing, and delay. This test evaluates whether turning vehicles interfere with through movement under fixed-time signal control, particularly when no dedicated turning lanes are available.

Setup:
Vehicles were generated from the North (NJ) and South (SJ) approaches with a mix of movements: 60% straight (JS or JN), 20% left turns (JE), and 20% right turns (JW). Routes were assigned randomly per vehicle. The default intersection layout was used, which does not include separate turning lanes.

Expected Results:
Turning vehicles may block following traffic when waiting for a gap or signal phase, leading to increased queue lengths and delays. Without turning lanes, even low proportions of turning traffic could impact the throughput of straight-moving vehicles.

Observation(s):
Shaded backgrounds indicate active green phases: blue for North–South and green for East–West traffic flow.



The North and South lanes show visible cycles of queue build-up and clearance, but with irregular patterns in comparison to previous straight-only experiments. Queue lengths often reach full capacity, and speed consistently drops during red phases and at points where turning interactions are likely. The presence of turning vehicles appears to reduce flow efficiency, as delays increase even during available green phases. These effects highlight how shared lanes without turning priority can lead to blocking and increased waiting times.

3.10 Dynamic Light Timing Test

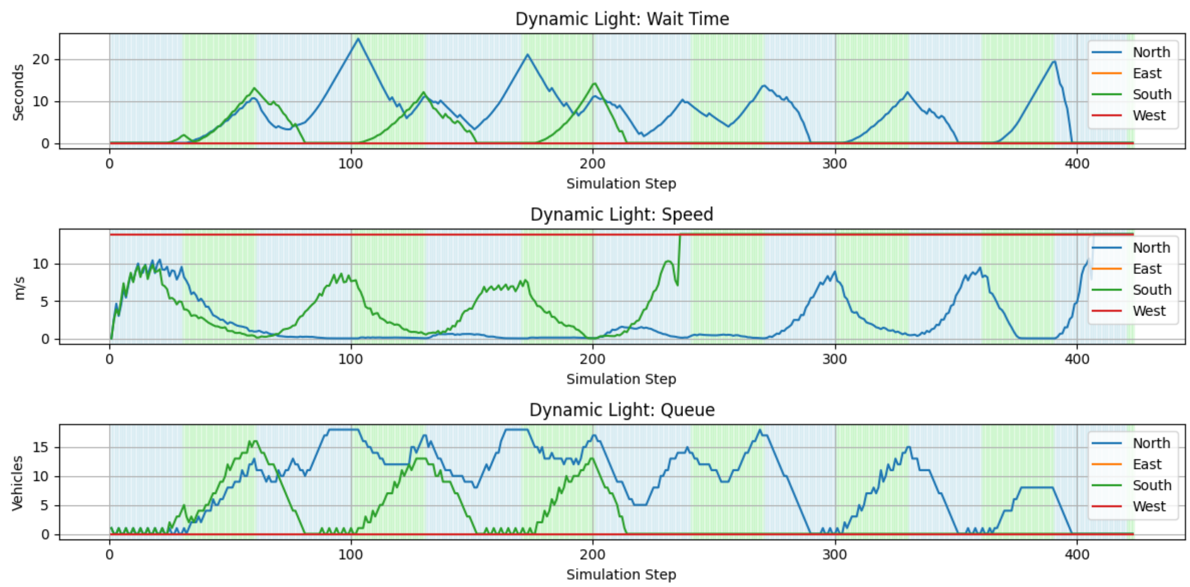
Purpose:
To evaluate whether a simple dynamic signal control method can improve traffic flow by extending green time based on real-time queue length. The goal is to test whether fewer phase changes and better queue clearance can be achieved compared to fixed-duration signals.

Setup:
(Similar to 3.9) Vehicles were introduced from the North (NJ) and South (SJ) approaches with a mix of movements: 60% straight (JS or JN), 20% left (JE), and 20% right (JW).

A manual two-phase system was implemented, alternating green between North–South and East–West directions. Each green phase lasted 30 seconds but could be extended by up to 10 seconds if the total queue length on the active lanes exceeded a threshold of 5 vehicles. Phase changes were tracked to monitor system responsiveness.

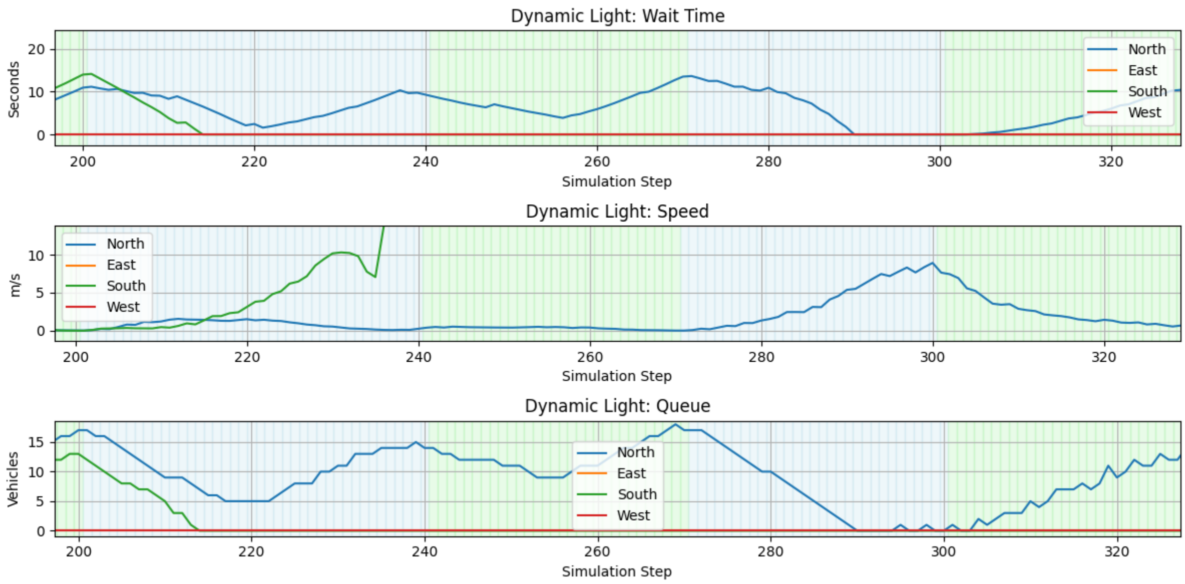
Expected Results:
Green phases were expected to be extended during periods of high congestion, allowing longer clearance time. This should reduce queue buildup and avoid unnecessary switching when lanes are still heavily loaded. Overall waiting times may be slightly reduced and phase changes less frequent.

Observation(s):
Shaded backgrounds indicate active green phases: blue for North–South and green for East–West traffic flow.



Across the full simulation, queues rarely reached full saturation, especially when compared to Experiment 3.9. Average speeds were generally higher and delays were lower, indicating that the adaptive extension helped prevent queues from growing too large. However, the overall traffic pattern was more irregular. Unlike the consistent build-up and release cycles seen in fixed-timing control, the dynamic logic introduced variability in phase lengths, which led to a less predictable rhythm in queue lengths, speeds, and waiting times.

Zooming in on a section:



Queue and wait time patterns show effective periodic clearance, with fewer abrupt transitions. The zoomed-in plot (simulation steps 200–320) highlights how the phase from step 200 to 240 was extended to 40 seconds due to queue length exceeding the threshold. In contrast, the green phase from step 270 to 300 was not extended, as the active lane queues had already reduced. These results confirm that the logic correctly adapts to conditions and can prevent premature switching.