Milestone 6: Sensitivity and Scenario Analysis

Fatih Kurt

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Contents

1 Introduction

In this milestone, sensitivity analysis and scenario analysis are performed to evaluate the robustness and adaptability of the traffic simulation model. The primary objective is to understand how changes in critical input parameters, such as vehicle acceleration and the number of cars, influence key system outputs like average queue length, average speed, average wait time, and the number of stopped cars.

Sensitivity analysis focuses on examining how small variations in the acceleration parameter affect the simulation outcomes, providing insights into the model's stability. Scenario analysis explores different traffic conditions by altering both the acceleration and the number of cars, representing realistic variations such as heavy traffic and smoother driving behaviors.

Through these analyses, the project aims to deepen the understanding of agent-based traffic dynamics and ensure that the model remains reliable across a range of plausible operating conditions.

2 Definitions and Terms

2.1 Sensitivity Analysis

Sensitivity analysis refers to the process of systematically varying key input parameters of a model to observe and quantify their impact on the outputs. In this project, sensitivity analysis is applied by slightly increasing or decreasing the acceleration parameter to determine how sensitive traffic performance metrics are to small changes in driver behavior.

2.2 Scenario Analysis

Scenario analysis involves creating distinct hypothetical situations by adjusting multiple parameters simultaneously to explore the behavior of the system under different conditions. In this project, scenarios are defined by varying both the acceleration setting and the number of cars on the road to simulate different traffic densities and driving styles.

2.3 Key Terms

- **Average Queue Length**: The mean number of cars waiting at intersections over time.
- **Average Speed**: The mean speed of all cars in the simulation during a run.
- **Average Wait Time**: The average amount of time cars spend stopped during their journey.
- **Number of Stopped Cars**: The number of cars with zero speed at any given simulation tick.
- **Acceleration**: The rate at which cars increase their speed when conditions allow.
- **Baseline Scenario**: A normal traffic situation with default acceleration and car numbers.
- **Optimistic Scenario**: A lighter traffic scenario with fewer cars and smoother acceleration.

- **Pessimistic Scenario**: A heavy traffic scenario with more cars and more aggressive acceleration.

3 Methodology

3.1 Sensitivity Analysis Approach

For sensitivity analysis, the acceleration parameter was selected due to its direct impact on vehicle movement, queue formation, and overall traffic flow. Small variations of $\pm 10\%$ and $\pm 20\%$ were applied relative to the default acceleration value used in the baseline model. The goal was to observe how minor adjustments in acceleration influenced the key traffic metrics: average queue length, average speed, average wait time, and the number of stopped cars. Each adjusted acceleration value was tested through full simulation runs to record comparative data.

3.2 Scenario Analysis Approach

For scenario analysis, two parameters were varied simultaneously: acceleration and the number of cars. Three distinct scenarios were designed:

- **Baseline Scenario**: Default acceleration and 50 cars.
- **Optimistic Scenario**: Reduced acceleration (smoother driving behavior) and 40 cars, representing lighter traffic and calmer driver actions.
- **Pessimistic Scenario**: Increased acceleration (more aggressive driving behavior) and 60 cars, representing congested conditions and aggressive starts.

Each scenario was run independently, and the same traffic performance metrics were collected for cross-scenario comparison.

4 Results

4.1 Sensitivity Analysis Results

The sensitivity analysis examined how variations in the acceleration parameter affected key traffic metrics. Five test runs were conducted with acceleration values of 0.0792, 0.0891, 0.099 (baseline), 0.1089, and 0.1188.

The following table summarizes the results:

Table 1: Sensitivity Analysis Summary

Test	Acceleration	Avg. Queue Length	Avg. Speed	Avg. Wait Time	Avg. Stopped Cars
Test 1	0.0990	1.4396	0.5881	1.6370	13.03
Test 2	0.0891	1.5028	0.5695	1.6670	13.60
Test 3	0.0792	1.4923	0.5838	1.8390	13.50
Test 4	0.1089	1.7924	0.6324	2.2910	16.21
Test 5	0.1188	1.8641	0.6402	2.3972	16.89

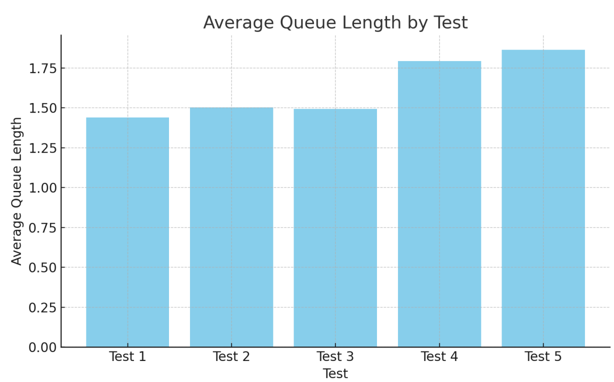

Figure 1: Average Queue Length vs. Acceleration

Interpretation: As acceleration increases, average speed also rises, which is expected. However, this comes at a cost: queue lengths, wait times, and the number of stopped cars all increase significantly. This indicates that while faster acceleration improves local vehicle flow, it likely causes increased

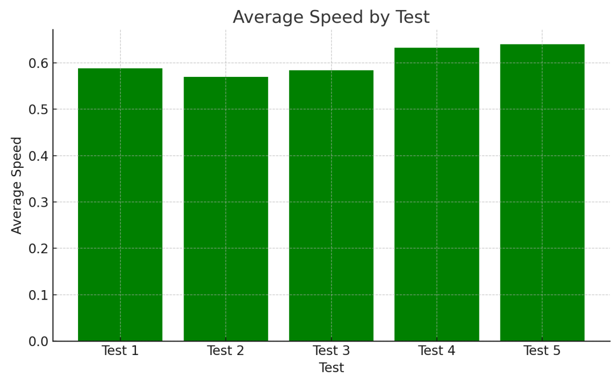

Figure 2: Average Speed vs. Acceleration

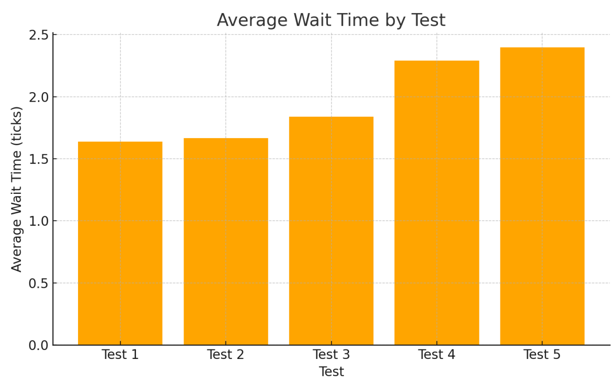

Figure 3: Average Wait Time vs. Acceleration

disruption at intersections and bottlenecks, degrading overall traffic performance.

The results show that the system is moderately sensitive to acceleration changes. Even small adjustments (±10%) lead to noticeable shifts in traffic efficiency, especially in congestion-related metrics.

4.2 Scenario Analysis Results

Three scenarios were constructed to explore how simultaneous variations in acceleration and vehicle count impact traffic performance:

- **Baseline Scenario:** Acceleration = 0.099, 50 cars. This reflects normal traffic with standard driver behavior.

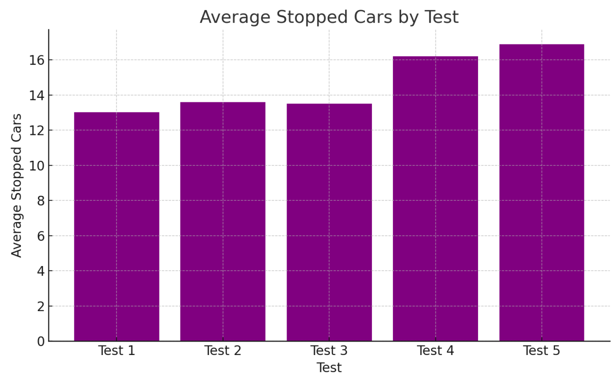

Figure 4: Average Stopped Cars vs. Acceleration

- **Optimistic Scenario:** Acceleration = 0.0792, 40 cars. This models a smoother, less congested system with slower acceleration and fewer vehicles on the road.
- **Pessimistic Scenario:** Acceleration = 0.1188, 60 cars. This models heavier traffic with more aggressive acceleration behaviors, simulating a worst-case condition.

These combinations were chosen to investigate the interaction between vehicle density and acceleration behavior — two core variables in traffic systems that can significantly influence congestion, throughput, and flow stability.

Table 2: Scenario Analysis Summary

Scenario	**Acceleration**	**# Cars**	**Avg. Queue**	**Avg. Speed**	**Avg. Wait Time**	**Avg. Stopped Cars**
Baseline	0.0990	50	1.4396	0.5881	1.6370	13.03
Optimistic	0.0792	40	1.1883	0.5863	1.4096	10.73
Pessimistic	0.1188	60	1.6847	0.6108	1.9557	15.24

Discussion: The optimistic scenario achieved the best performance across nearly all metrics: the lowest average queue length, wait time, and number of stopped cars. The average speed remained comparable across all scenarios, indicating that overall flow was not sacrificed for smoother traffic. In contrast, the pessimistic scenario showed degraded performance in all

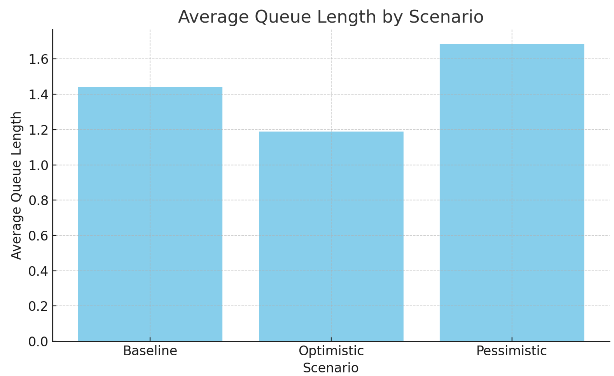

Figure 5: Average Queue Length by Scenario

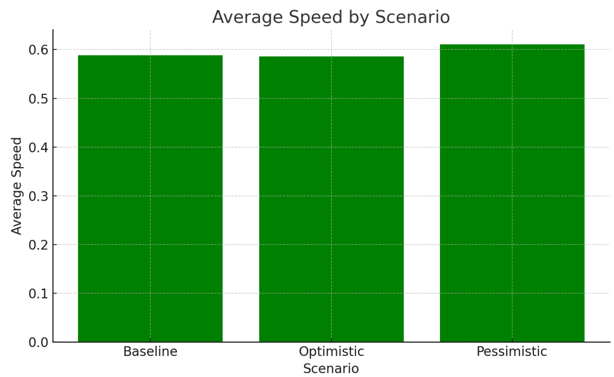

Figure 6: Average Speed by Scenario

congestion-related metrics. This highlights that higher acceleration rates paired with increased vehicle density can worsen traffic flow even when individual vehicles move faster.

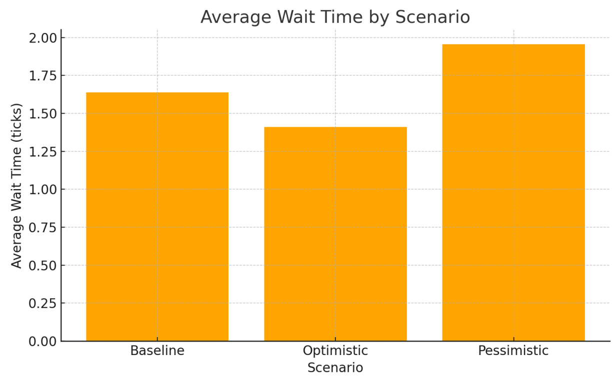

Figure 7: Average Wait Time by Scenario

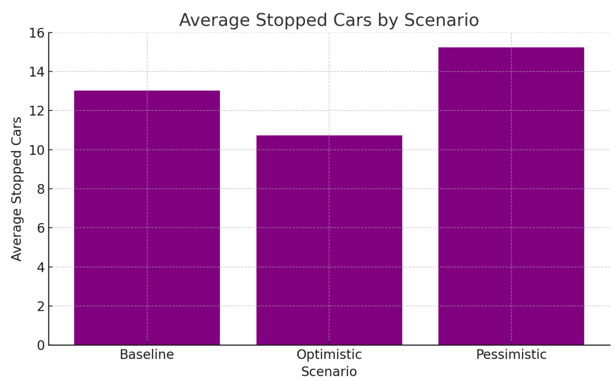

Figure 8: Average Stopped Cars by Scenario

5 Discussion

The simulation results from both sensitivity and scenario analyses provide meaningful insights into the dynamics of traffic flow under varying acceleration rates and vehicle densities.

Implications of Findings

The sensitivity analysis revealed that while increasing acceleration improves the average speed of vehicles, it also leads to higher queue lengths, increased wait times, and more frequent stops. This suggests a trade-off between individual vehicle performance and system-wide traffic efficiency. Even modest changes in acceleration (as little as $\pm 10\%$) showed measurable impacts, underscoring the importance of fine-tuning this parameter in autonomous vehicle control strategies.

The scenario analysis further demonstrated that traffic flow is highly sensitive to the interplay between driver behavior (as modeled by acceleration) and vehicle count. The optimistic scenario, with fewer cars and gentler acceleration, consistently outperformed the other scenarios in congestion metrics without compromising average speed. Conversely, the pessimistic case—featuring more vehicles and aggressive acceleration—produced the worst congestion, highlighting that aggressive driving behaviors do not necessarily translate to better overall throughput.

Insights into Model Behavior

The agent-based nature of the simulation made it clear that emergent system behavior can diverge significantly from individual agent goals. Although faster acceleration enables a vehicle to reach its destination sooner in isolation, it contributes to more frequent stopping and blocking when applied across a dense population of agents. The presence of intersections and fixed signal phases further compounded this effect, illustrating how local optimizations can create systemic inefficiencies.

Moreover, the relative stability of average speed across all scenarios—despite large differences in congestion metrics—suggests that average speed alone may not be a reliable proxy for traffic quality. Instead, metrics like queue length and wait time provide a more complete picture of system efficiency and user experience.

Limitations and Assumptions

The model assumes simplified driving rules and fixed intersection behaviors. For example, cars always accelerate in the same manner and follow fixed logic at intersections. Real-world drivers may exhibit more nuanced behavior influenced by surrounding traffic, variable acceleration profiles, and adaptive decision-making.

Additionally, the simulation does not incorporate stochastic variability in route selection, driver error, or environmental conditions (e.g., road surface, weather), which could affect traffic patterns. The grid layout is static, and the signal timing is not optimized or adaptive, limiting the exploration of more realistic control schemes.

Lastly, while the acceleration parameter was varied, other parameters such as turn frequency, car goal logic, or light coordination were held constant. This could mask deeper interactions and feedback loops within the system that might emerge under broader testing conditions.

6 Conclusion

Summary of Key Takeaways

This milestone explored how traffic flow is affected by variations in acceleration and vehicle density through both sensitivity and scenario analyses. The results demonstrated that:

- Small changes in acceleration significantly influenced traffic congestion metrics, including queue length, wait time, and number of stopped cars.
- Higher acceleration increased average speed but worsened congestion-related outcomes, highlighting a trade-off between local and global performance.
- Scenario analysis showed that lower acceleration combined with fewer vehicles (optimistic scenario) yielded the best overall traffic performance.
- Average speed remained relatively stable across tests, reinforcing that it should not be the sole metric for evaluating traffic efficiency.

These findings reinforce the utility of agent-based simulation in modeling emergent behavior in traffic systems and provide data-driven insights for designing better vehicle control strategies and traffic policies.

Recommendations for Future Work

To build upon these results, the following improvements are recommended for future simulations:

- Introduce adaptive traffic light control or dynamic signal coordination to simulate more realistic traffic management systems.
- Extend the parameter space to include goal-switching delays, varying route logic, and the introduction of turning behaviors at intersections.
- Implement a broader range of agent types (e.g., cautious vs. aggressive drivers) to model more heterogeneous traffic scenarios.

- Incorporate stochastic variability or real-world traffic datasets to validate the simulation's realism.
- Analyze additional performance metrics such as throughput, travel time distribution, and intersection utilization.

These extensions would enhance the realism and applicability of the model, ultimately contributing to more robust insights for the design and management of traffic systems with autonomous or mixed fleets.

7 References

References

[1] U. Wilensky and W. Rand, *An Introduction to Agent-Based Modeling: Modeling Natural, Social, and Engineered Complex Systems with NetLogo*. MIT Press, 2015.

[2] U. Wilensky, "NetLogo," Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL, 1999. [Online]. Available: `http://ccl.northwestern.edu/netlogo/`

[3] U. Wilensky and W. Rand, "NetLogo Traffic Grid Goal Model," Northwestern University, Center for Connected Learning and Computer-Based Modeling. [Online]. Available: `http://ccl.northwestern.edu/netlogo/models/TrafficGridGoal`

[4] NetLogo User Manual, "Programming Guide," [Online]. Available: `https://ccl.northwestern.edu/netlogo/docs/`

A Appendices

Appendix A: Supplementary Simulation Data

Full CSV exports of the following metrics were generated for each test run and stored in a structured directory:

- `average-queue-length.csv`
- `average-speed-of-cars.csv`
- `average-wait-time-of-car.csv`
- `stopped-cars.csv`

Each file contains tick-wise recordings of the respective metric and was used to compute the mean values presented in the report. Files are labeled by test or scenario number for clarity.

Appendix B: Code Snippet for Data Recording in NetLogo

Below is an example of the procedure used in NetLogo to record data at every simulation tick:

```
to record-data  ;; turtle procedure
  ifelse speed = 0 [
    set num-cars-stopped num-cars-stopped + 1
    set wait-time wait-time + 1
  ]
  [ set wait-time 0 ]
end
```

Data was then exported manually using the NetLogo plotting interface and saved as CSV for external analysis in Python.

Appendix C: Key Terms and Definitions

- **Acceleration:** The rate at which a car increases its speed in the simulation. Used as a tunable parameter to model different driving behaviors.
- **Queue Length:** The number of vehicles that are waiting (speed = 0) at any given time, averaged across intersections.
- **Average Wait Time:** The mean duration (in ticks) that cars remain stopped due to congestion or signals.
- **Average Speed:** The average velocity of all moving cars in the system.
- **Stopped Cars:** The number of cars that have a speed of zero at a given tick, averaged over time.
- **Scenario Analysis:** A method used to examine outcomes under combinations of parameters representing different future conditions.
- **Sensitivity Analysis:** A method to study how small changes in a single parameter affect the model's outputs.