

Scalable Simulation and Evaluation of Adaptive Fuzzy Traffic Signal Controller under Multi-Scenario Urban Conditions

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1. PROBLEM STATEMENT

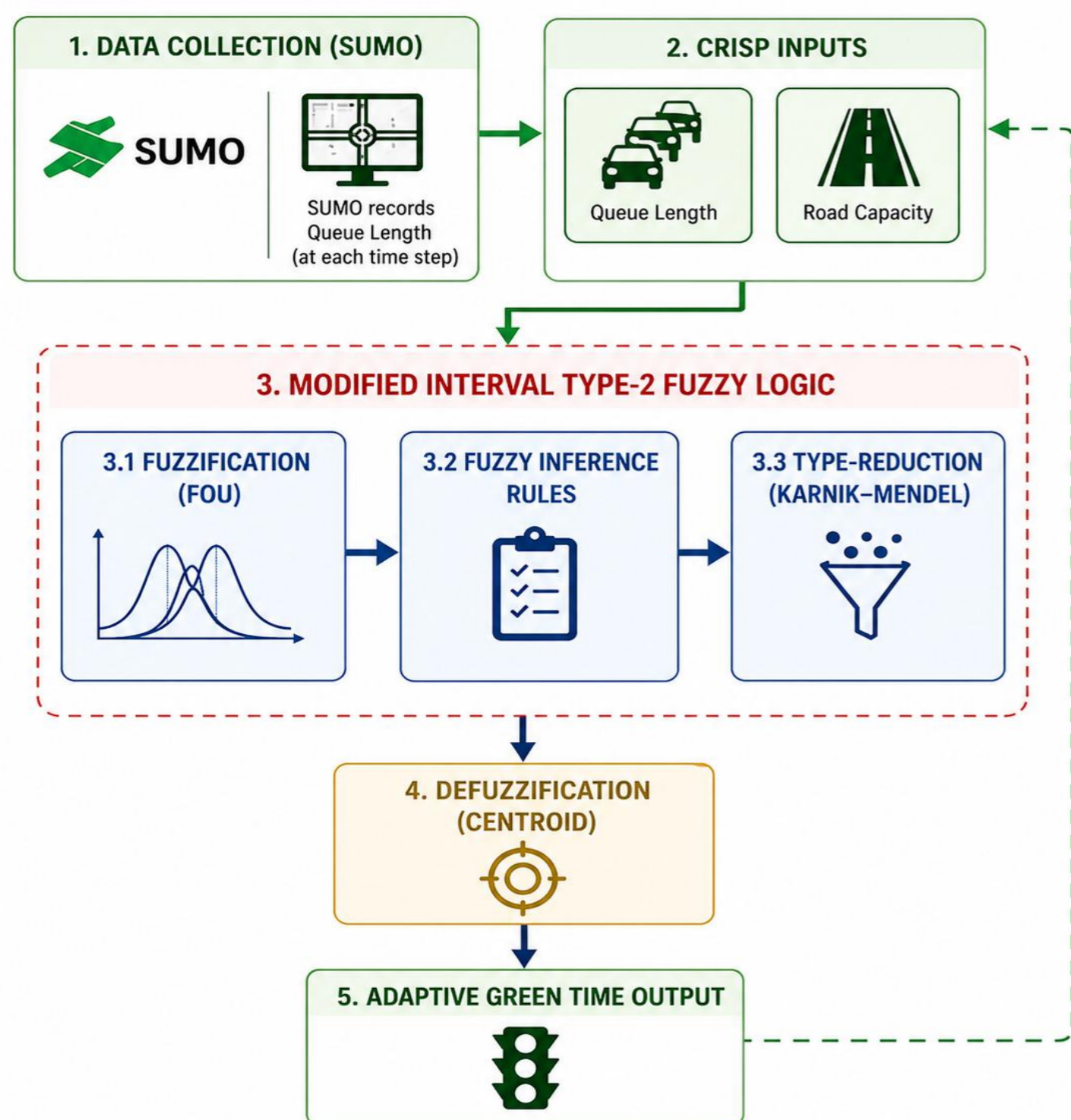
- Fixed-time traffic signals are inefficient in dynamic urban environments.
- They cannot adapt to real-time fluctuations and asymmetric traffic demand.
- This leads to longer queues, increased delay, time loss, fuel consumption, and emissions.

2. PROPOSED APPROACH (MIT2FL)

Modified Interval Type-2 Fuzzy Logic (MIT2FL) handles uncertainty and adapts signal timing in real time.

- Models uncertainty using Footprint of Uncertainty (FOU)
- Applies Karnik–Mendel type reduction
- Generates adaptive green-time output

MIT2FL ARCHITECTURE



3. SIMULATION SETUP

- SUMO-based simulation of a four-leg urban intersection
- Nine scenarios covering low, medium, and high demand
- Balanced and asymmetric traffic flows considered
- Evaluation metrics: queue length, waiting time, and time loss

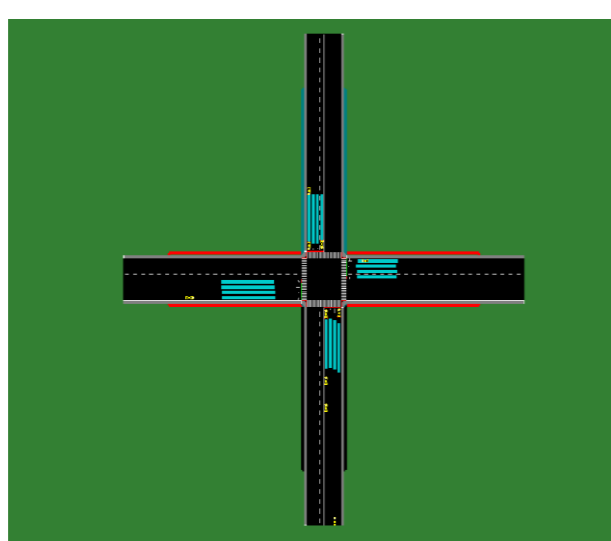


Figure 1a: SUMO Four-Leg Intersection Model

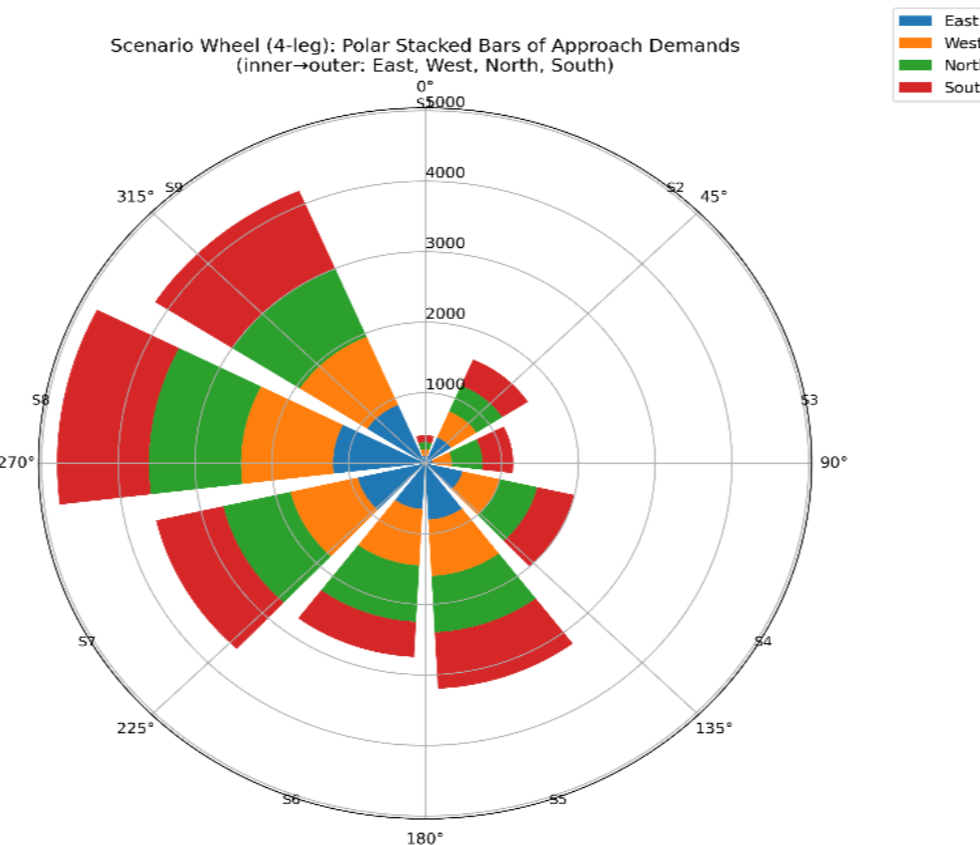
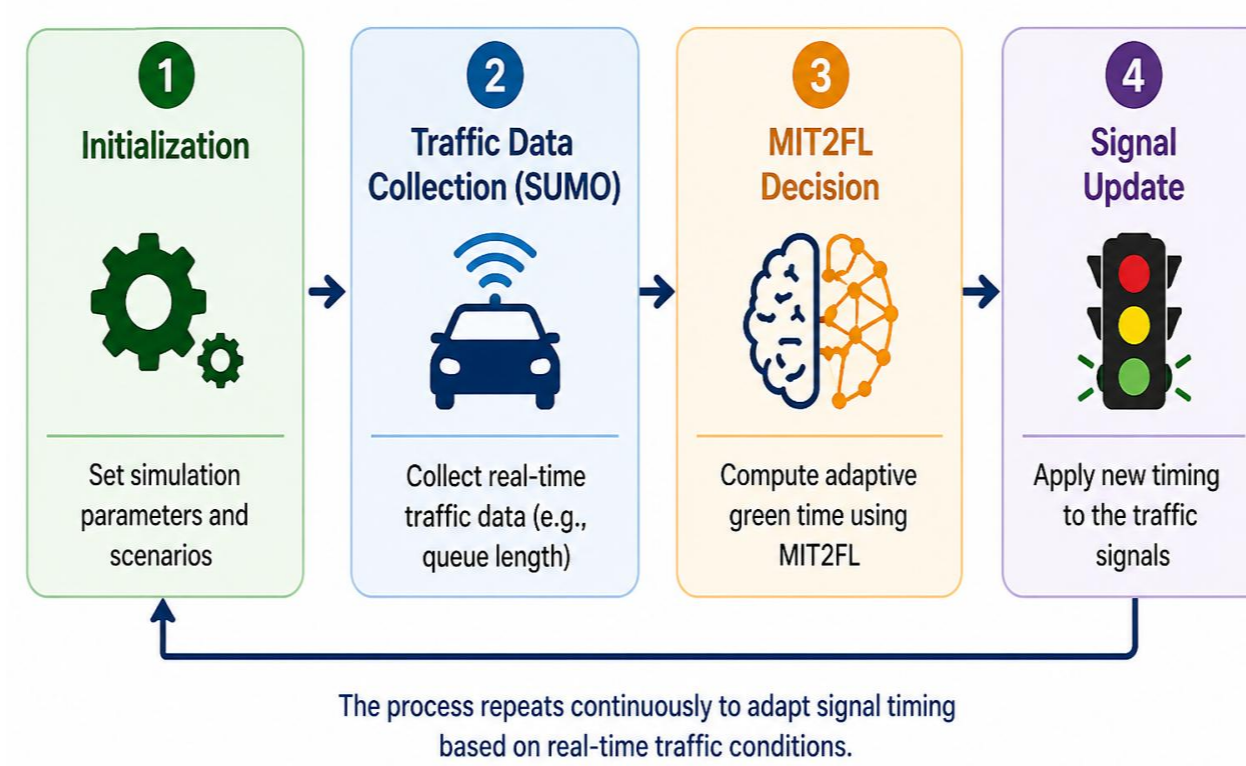


Figure 1b: Scenario Wheel (4-leg).

4. WORKFLOW OF MIT2FL CONTROLLER



5. RESULTS AND DISCUSSION

- MIT2FL significantly reduces queue length compared to conventional methods
- Best performance observed under high and asymmetric traffic conditions
- Improved stability and smoother traffic flow
- Faster response to real-time traffic variations

Traffic Demand	Scenario	MIT2FL	Modified Webster Method	Improvement Percentage of MIT2FL w.r.t MW
Low	S1	1.1801	2.6886	56.1%
	S2	8.5197	13.7882	38.2%
	S3	5.7511	7.5557	23.9%
Medium	S4	9.8706	15.0633	34.5%
	S5	21.5820	25.9672	16.9%
	S6	16.5812	23.6886	30.0%
High	S7	24.0799	27.2935	11.8%
	S8	23.5636	27.404	14.0%
	S9	24.1787	27.4706	12.0%

MIT2FL achieves lower queue lengths across all scenarios, with improvements up to 56.1% compared to Modified Webster. Performance gains remain consistent across low, medium, and high demand levels, confirming strong adaptability to dynamic traffic conditions.

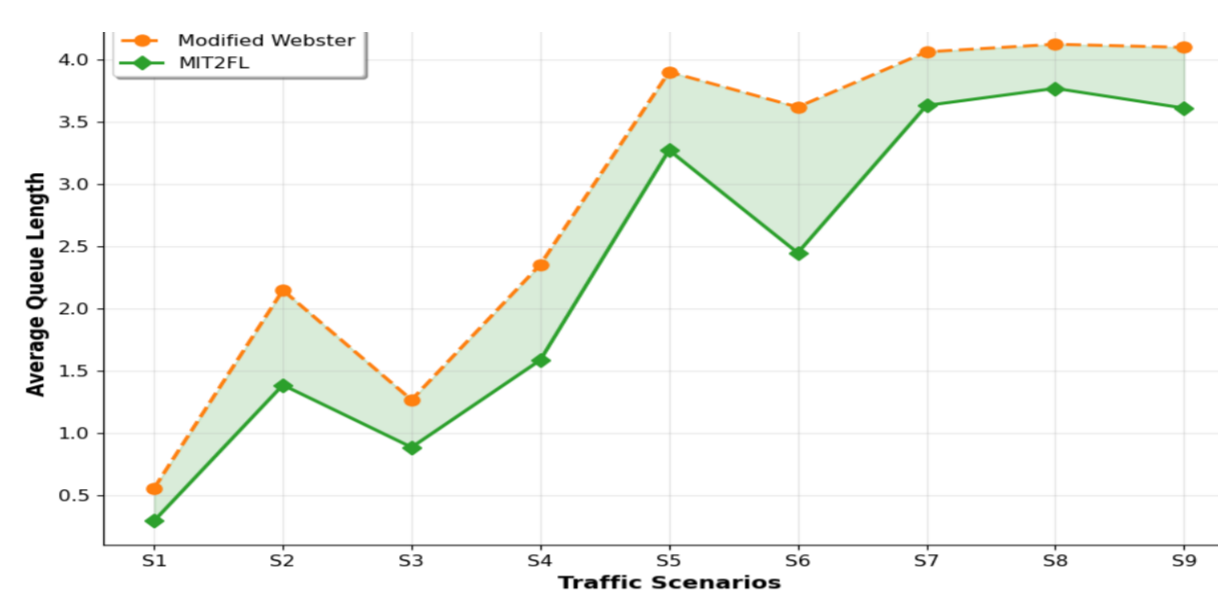


Figure 2: Queue Length Comparison: MIT2FL vs MW

KEY RESULT



MIT2FL reduced queue length by up to 56.1% compared with Modified Webster, with the strongest performance under medium, high, and asymmetric traffic conditions.

- MIT2FL reduces average queue length across all scenarios
- Maximum improvement of 56.1% compared with Modified Webster
- Strongest performance observed under medium and high demand
- Demonstrates better adaptability to dynamic traffic conditions

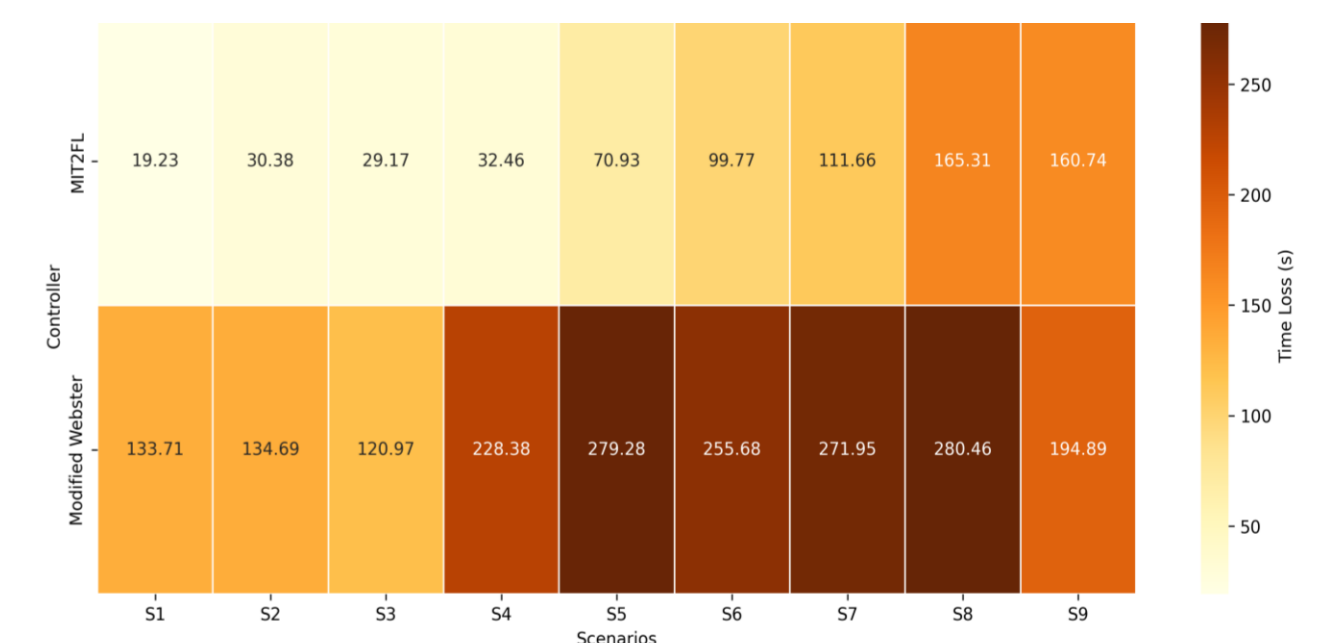


Figure 3: Average Vehicle Time Loss Heatmap

- MIT2FL achieves lower vehicle time loss in all scenarios
- Significant delay reduction under congested traffic conditions
- Improved efficiency in medium and high traffic demand
- Enhances overall traffic flow performance

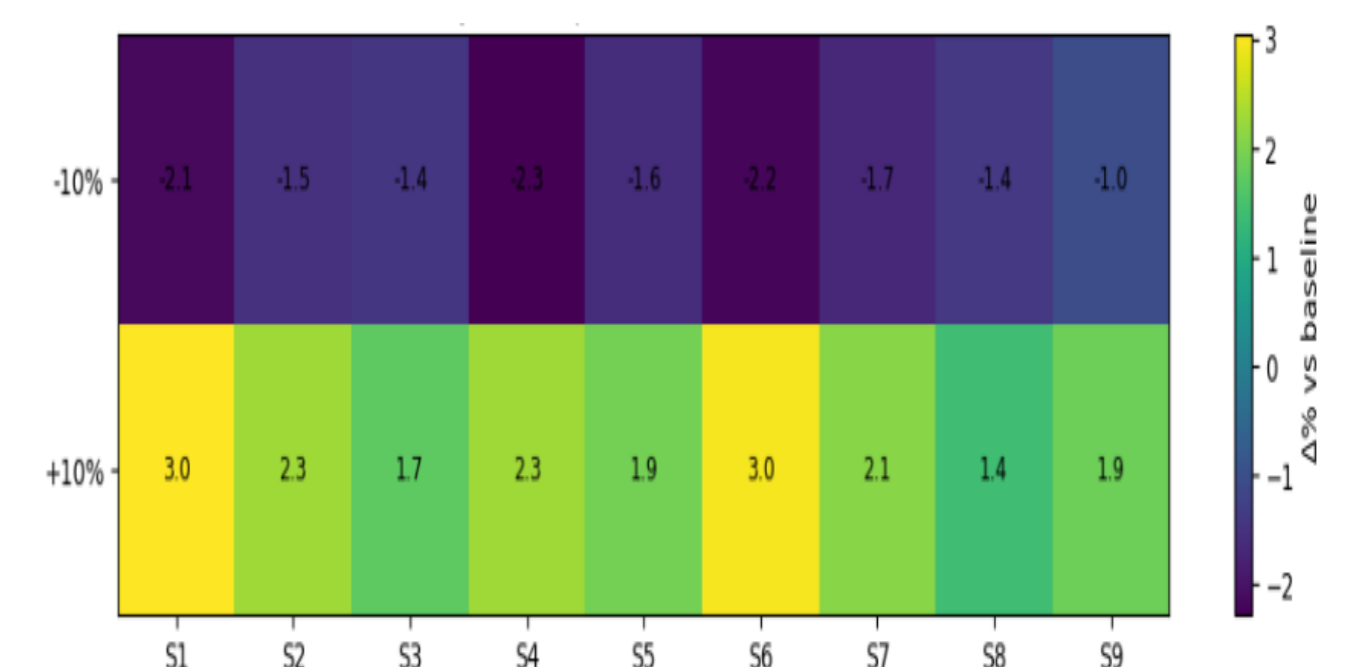


Figure 4: Sensitivity Analysis

- MIT2FL remains stable under $\pm 10\%$ traffic demand variation
- Performance improves under increased demand conditions
- Only minor degradation observed under reduced demand
- Confirms robustness in handling traffic uncertainty

6. CONCLUSION

MIT2FL improved adaptive traffic signal control across nine SUMO-based demand scenarios. Compared with Modified Webster, it reduced queue length and vehicle time loss, with stronger performance under medium, high, and asymmetric traffic conditions. These results show that interval type-2 fuzzy logic is a robust approach for uncertainty-aware urban signal control.