Zero-Shot Traffic Signal Control via Prophet Forecasting and Deep Q-Networks in SUMO Simulated Environments

A Thesis Proposal By

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Chapter 1

Introduction

Background of the study

Traffic congestion remains a critical challenge across major urban centers worldwide, with cities experiencing exponential growth in vehicle volumes that far exceed infrastructure capacity. Urban highways and arterial roads face daily traffic loads that can exceed their design capacity by 30-40%, creating cascading effects of economic losses, environmental degradation, and reduced quality of life for millions of commuters. Metro Manila exemplifies this global urban mobility crisis, with major corridors like EDSA accommodating over 400,000 vehicles daily despite being designed for only 300,000 vehicles (Presidential Communications Office, 2024).

While some portions of Metro Manila have recently adopted sensor-based signal controllers that respond to current traffic conditions, these reactive systems typically optimize for the immediate present and lack mechanisms to anticipate incoming congestion. By combining short-term traffic forecasts from Prophet with a signaling system based on Deep Q-Learning (DQN) and SUMO simulation, our approach shifts control from reactive responses to generalizable, proactive, and context-aware decision making. Rather than overfitting signal policies to specific intersections, our system aims to learn generalizable policies from training on a few representative intersections, enabling zero-shot deployment on unseen traffic environments.

Furthermore, the proposed system holds even greater potential in areas operating on fixed-timing schedules. These conventional setups, which cycle through pre-set intervals regardless of actual traffic demand, remain common across many parts of Metro Manila, including major avenues. Integrating forecasting and reinforcement learning of light signals into such environments can enhance efficiency, transforming static control points into intelligent intersections capable of adapting to both present and predicted traffic conditions.

Advances in data science and machine learning, especially in time series forecasting and reinforcement learning, offer new opportunities to improve traffic management. Facebook Prophet provides reliable forecasting for seasonal traffic patterns (Dieckmann, 2024), while Deep Q-learning enables adaptive decision-making in changing conditions through recent advances in deep reinforcement learning for traffic signal control (Bao et al., 2023). The Simulation of Urban Mobility (SUMO) offers a realistic testing environment for traffic optimization and reinforcement learning algorithms without affecting actual traffic. Together, these tools support a data-driven, proactive traffic control system that can anticipate congestion but also adapt in real time due to reinforcement learning training and simulation.

Problem Statement

Despite advances in traffic control systems, urban traffic management generally lacks an integrated pipeline that can forecast, model, and simulate traffic conditions to guide intelligent decision-making. Similar studies like Tranos et al. (2024) demonstrate zero-shot knowledge transfer in multi-agent reinforcement learning but focus exclusively on autonomous vehicle coordination at unsignalized intersections rather than predictive signal timing optimization. Combining short-term traffic forecasts with tools like SUMO for realistic simulation and Deep Q-learning for adaptive optimization could greatly improve traffic signal efficiency from individual intersections to coordinated multi-intersection networks, yet such integration remains absent in the local context. Specifically:

1. Limited simulation-based evaluation: SUMO's realistic traffic modeling and Deep Q-learning-based optimization remain largely unused for simulating actual domestic intersections and testing coordination strategies before implementation
2. Underutilization of traffic data: MMDA's historical traffic datasets are not being fully leveraged for predictive, forward-looking congestion management (Open Data Philippines, 2024)
3. Lack of predictive modeling: No official system exists for accurately forecasting short-term traffic trends along major Metro Manila corridors, especially with modern tools like Prophet
4. Outdated or purely reactive signal control: Many intersections still rely on fixed schedules or real-time reactive systems that cannot adapt to predicted traffic conditions
5. No pipeline exists for integrating traffic forecasting with reinforcement learning in a way that trains on a limited set of intersections and also generalizes to unseen intersections, especially with the current proposed pipeline. Existing approaches tend to optimize signal control per intersection, lacking adaptability and does not support transferability or zero-shot adaptations to new traffic layouts.

Project Objectives

To develop a forecast-driven reinforcement learning model that integrates traffic flow predictions from Prophet with SUMO-based simulation, enabling adaptive traffic light optimization along major intersections. Specifically, the group aims:

1. To model and simulate selected intersections in SUMO as training environments for the reinforcement learning agent using forecasted traffic demand.
2. To leverage historical traffic datasets from MMDA and other sources to create predictive, forward-looking congestion management models.

3. To develop a short-term forecasting system capable of accurately predicting traffic volumes and congestion patterns along key Metro Manila corridors.
4. To design and implement generalizable signal control policies using deep reinforcement learning (Deep Q-Learning), with a focus on zero-shot adaptability to traffic conditions at intersections not included in the training set.
5. To evaluate the learned policy's zero-shot performance on simulated unseen intersections, comparing against fixed-timing and reactive baselines. using the ISO/IEC 25010 software quality characteristics of Functional Suitability, Performance Efficiency, Usability, and Reliability.

Significance of the Study

This study advances urban traffic management by developing a forecast-driven reinforcement learning system to optimize traffic signals along major intersections. The zero-shot capability represents a significant advancement, enabling rapid deployment of efficient traffic systems across urban environments without site-specific retraining. The results will address current inefficiencies in congestion control and prove beneficial to the following:

Traffic management agencies like the MMDA can leverage the system's predictive capabilities to better plan and coordinate traffic signals, enabling a shift from reactive to anticipatory control and improving overall traffic flow. Commuters benefit from more accurate traffic forecasts that support better travel planning and reduced delays, potentially saving both time and fuel.

Urban planners and policymakers will find value in data-driven insights that highlight congestion hotspots, guiding infrastructure development and policy decisions. From an academic perspective, this research demonstrates the effective integration of machine learning, forecasting, and simulation techniques to solve real-world traffic challenges, laying a foundation for future innovations in smart traffic systems.

Finally, by optimizing traffic flow and reducing stop-and-go conditions, the system contributes to environmental sustainability through lower emissions and offers economic benefits by improving fuel efficiency and commuter productivity.

Scope and Delimitations

Scope

In forecasting, the study focuses on short-term traffic forecasting (up to 24 hours ahead) using data from selected intersections along using Prophet.

Historical traffic volume data will be obtained primarily from publicly available MMDA records or through Freedom of Information (FOI) requests.

SUMO will be used to create digital models of selected intersections for training, including traffic flow patterns, lane configurations, and signal phases. In applying the final product or model, intersections unseen by the model will also be modeled and simulated in SUMO.

The Deep Q-Learning (DQN) based reinforcement learning agent will be trained in SUMO using forecasted traffic demand at selected intersections and then tested for zero-shot generalization to unseen intersection layouts and traffic profiles that have similar qualities to the training set

Model evaluation will include both forecasting accuracy metrics (e.g., MAE, RMSE) and simulation-based performance metrics aligned with the ISO/IEC 25010 software quality characteristics, specifically Functional Suitability, Performance Efficiency, Usability, and Reliability. (International Organization for Standardization, 2023)

Delimitations

The research will not involve live deployment or direct control of real-world traffic signals; all testing will be conducted within a simulated SUMO environment.

Real-time, continuous data collection will not be implemented; only historical datasets will be used for model training and evaluation.

External, unstructured factors such as road accidents, weather conditions, or construction activities will be excluded unless explicitly included in the dataset.

For training, the scope is limited to the selected intersections, with results expected to generalize to other road networks or intersections that have similar attributes to the training set

The study will focus on vehicle traffic volume and signal timing optimization; it will not address pedestrian flow, public transport scheduling, or integration with adaptive tolling systems and other similar infrastructure. Adapting the resulting zero-shot model is limited only to intersections or thoroughfares with similar attributes, vehicle flow, complexity as the intersections used for training.

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