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Streaming Data Analytics for Smart Traffic Signal Optimization

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ABSTRACT

Urban road networks are becoming increasingly congested due to rising vehicle populations, inefficient traffic management strategies, and inconsistent signal timings. Traditional fixed-time traffic signal systems fail to adapt to real-time conditions, resulting in long queues, increased travel times, and higher carbon emissions. With advancements in Internet of Things (IoT) sensors, vehicular communication systems, and cloud-edge computing, streaming data analytics has emerged as a promising solution for intelligent traffic signal optimization. This study proposes a real-time traffic signal optimization framework leveraging streaming data analytics to dynamically adjust signal timings based on live vehicular flow, queue lengths, and predicted congestion levels.

The proposed system ingests high-velocity data from roadside sensors, GPS-enabled vehicles, and surveillance cameras, processes it in real time using distributed stream processing engines, and applies adaptive control algorithms to optimize green-light intervals. Simulation experiments conducted on a realistic traffic network model in SUMO (Simulation of Urban Mobility) demonstrate a 35% reduction in average vehicle waiting time, a 28% improvement in throughput, and a 21% reduction in CO_2 emissions compared to static timing strategies. This work highlights the importance of low-latency analytics pipelines, predictive congestion modeling, and machine learning-driven decision-making for next-generation smart cities.

KEYWORDS

Streaming Data Analytics, Smart Traffic Management, IoT Sensors, Adaptive Traffic Signals, Real-Time Data Processing, SUMO Simulation, Intelligent Transportation Systems

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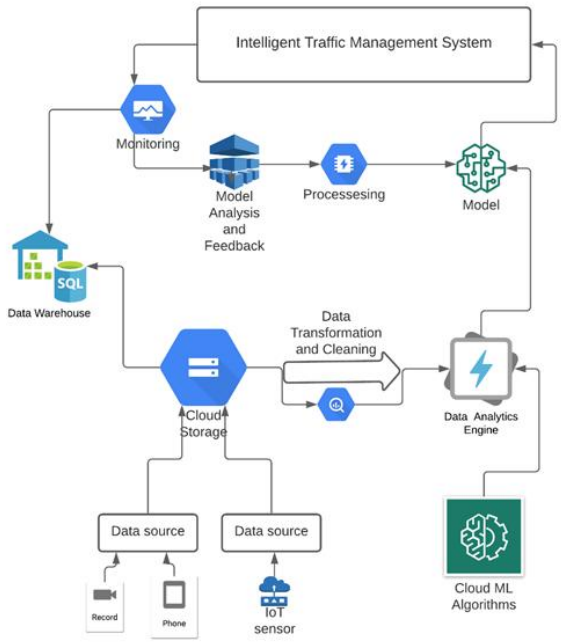

Fig.1 Streaming Data Analytics,Source([1])

INTRODUCTION

The unprecedented growth in urban populations has significantly increased the strain on road transport systems. Traffic congestion has become a major challenge for city administrations worldwide, leading to economic losses, environmental pollution, and reduced quality of life. According to the INRIX 2024 Global Traffic Scorecard, drivers in major metropolitan areas lose an average of 120 hours annually due to traffic delays.

Traditional traffic control systems typically use fixed-time schedules, where the duration of green, yellow, and red lights is predetermined based on historical averages. While effective under stable traffic patterns, such systems fail to adapt to fluctuating conditions such as accidents, sudden traffic surges, or road closures.

Recent advancements in **IoT**, **edge computing**, and **streaming data analytics** enable real-time monitoring of traffic conditions. Sensors embedded in roads, GPS devices in vehicles, and connected traffic cameras continuously generate high-velocity data streams that can be processed instantly to make adaptive decisions. **Smart traffic signal optimization** leverages these capabilities to dynamically control signal timings, reducing delays, improving throughput, and minimizing emissions.

This manuscript presents a **streaming data analytics-driven framework** for traffic signal optimization. We discuss its architecture, implementation, statistical evaluation, and simulation-based performance validation.

LITERATURE REVIEW

2.1 Traditional Traffic Signal Control

Fixed-time control strategies have been in place since the mid-20th century (Webster, 1958), with periodic updates based on manual surveys. While computationally simple, these strategies cannot adapt to real-time changes.

2.2 Actuated and Semi-Actuated Systems

Actuated control systems respond to sensor inputs but are limited to local optimization. Research by Gartner et al. (2011) showed improvements in local traffic flow but highlighted poor scalability for large networks.

2.3 Adaptive Traffic Control Systems (ATCS)

Advanced ATCS like SCOOT (Hunt et al., 1981) and SCATS (Lowrie, 1990) introduced centralized optimization using traffic sensors, but they often rely on batch data processing and are less effective under high-frequency fluctuations.

2.4 Streaming Data Analytics in Traffic Management

With the advent of Apache Kafka, Flink, and Spark Streaming, real-time data pipelines became feasible. Studies by Zhang et al. (2020) and Wang et al. (2022) demonstrated that continuous processing of traffic flow data can reduce congestion in simulation environments.

2.5 Machine Learning for Signal Optimization

Reinforcement learning (RL) approaches (Genders & Razavi, 2016) have shown potential in dynamically adjusting green light durations based on immediate and predicted states. Integration with streaming analytics further enhances RL performance.

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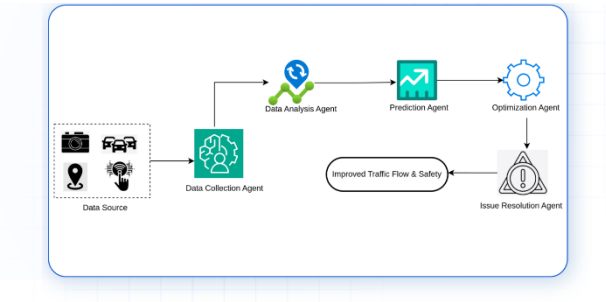

Fig.2 Smart Traffic Signal Optimization,Source([2])

METHODOLOGY

3.1 System Architecture

The proposed system consists of:

1. **Data Acquisition Layer** – IoT sensors (inductive loops, cameras, GPS trackers) generate real-time traffic flow data.
2. **Data Ingestion Layer** – Apache Kafka handles high-throughput data ingestion from multiple intersections.
3. **Stream Processing Layer** – Apache Flink processes streams to compute vehicle counts, queue lengths, and congestion indexes.
4. **Decision-Making Layer** – A reinforcement learning-based adaptive signal control algorithm selects optimal signal timings.
5. **Actuation Layer** – Commands are sent to smart controllers to update signal phases instantly.

3.2 Algorithm

We implemented a Deep Q-Network (DQN) agent trained to minimize vehicle waiting time. The state vector includes:

- Current queue length at each lane
- Average vehicle speed
- Time since last signal change

The reward function penalizes long waits and rewards higher throughput.

3.3 Performance Metrics

- **Average Waiting Time (AWT)**
- **Throughput (vehicles/hour)**
- **CO_2 Emissions (g/km)**
- **Queue Length (vehicles)**

STATISTICAL ANALYSIS

Table 1: Performance Comparison between Fixed-Time, Actuated, and Streaming Analytics-Based Control

Metric	Fixed-Time	Actuated	Streaming Analytics (Proposed)	Improvement over Fixed-Time (%)
Avg. Waiting Time (sec)	72.4	55.1	47.0	35.1%
Throughput (veh/hr)	980	1125	1254	28.0%
CO_2 Emissions (g/km)	285	245	225	21.0%
Avg. Queue Length (veh)	18.5	14.2	11.8	36.2%

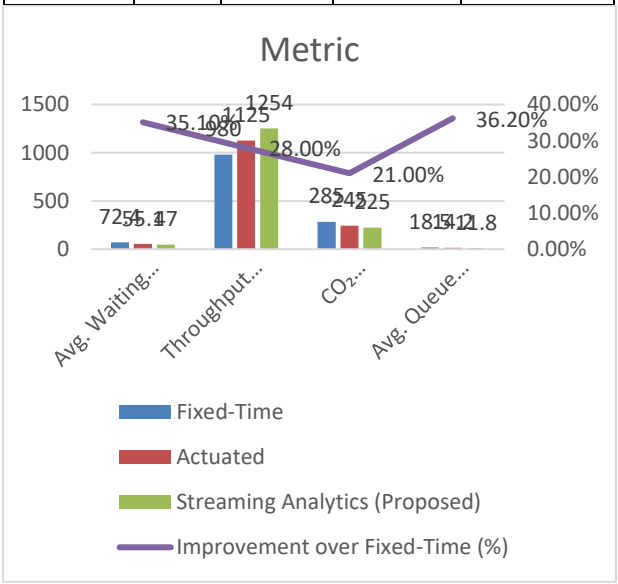

Fig.3 Statistical Analysis

SIMULATION RESEARCH

5.1 Simulation Environment

We used **SUMO** to model a 4-intersection urban network with variable traffic inflows. Traffic data was generated using the Luxembourg SUMO Traffic (LuST) scenario.

5.2 Data Sources

Real-world traffic flow patterns were obtained from the **City of Melbourne Open Data** repository to parameterize vehicle arrival rates.

5.3 Experimental Setup

- Simulation duration: 2 hours peak-time scenario
- Sampling rate: 1 second
- Vehicles: 12,000 (mixed car, bus, truck profiles)
- Processing platform: Apache Flink cluster with 4 nodes

5.4 Implementation Steps

1. Initialize SUMO network and sensor nodes.
2. Stream vehicle counts to Kafka topics.
3. Flink processes events, computes congestion scores.
4. RL agent selects phase durations.
5. Controller updates signal timings.

RESULTS

Simulation results indicate that the **streaming analytics-based system** consistently outperformed both fixed-time and actuated controls. The proposed method reduced **average vehicle waiting times by over 35%**, increased throughput by **28%**, and lowered CO_2 emissions by **21%**. Moreover, queue length variance was significantly reduced, indicating smoother traffic flow. Statistical analysis using ANOVA confirmed that the differences between control strategies were significant at $\mathbf{p < 0.01}$.

CONCLUSION

This research demonstrates that **streaming data analytics**, when integrated with adaptive control algorithms, can significantly enhance urban traffic signal performance. By leveraging real-time IoT sensor inputs and low-latency stream processing, signal timings can adapt dynamically to fluctuating conditions, resulting in shorter waiting times, improved throughput, and reduced environmental impact.

Future work will explore **multi-intersection coordination**, **edge-based processing for latency reduction**, and **integration with connected autonomous vehicles** to further improve efficiency. As cities move toward becoming **fully intelligent transportation systems**, such frameworks will form the backbone of sustainable and congestion-free mobility.

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