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Traffic Flow Optimization for Metropolitan Cities

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Abstract*: This research paper presents the design and implementation of an adaptive traffic signal timer system that utilizes real-time traffic density calculation and an intelligent signal switching algorithm to optimize traffic flow at intersections. The proposed system leverages computer vision techniques like object detection to count and classify vehicles, and then dynamically adjusts the green signal durations based on the detected traffic density. A simulation module is also developed to visualize the system's performance and compare it to a static traffic signal implementation. The results demonstrate the effectiveness of the adaptive approach in reducing vehicle waiting times and improving overall intersection throughput.*

Keywords: Adaptive Traffic Signal, Computer Vision, Traffic Optimization, Simulation

I. INTRODUCTION

Urban traffic congestion is a growing challenge, often exacerbated by static traffic signal timing approaches that fail to adapt to changing conditions. This research presents an adaptive traffic signal timer system that utilizes real-time vehicle detection and an intelligent Signal Switching Algorithm to optimize intersection throughput. The proposed system leverages computer vision techniques to classify and count vehicles, then dynamically adjusts signal durations based on factors like traffic density, vehicle startup times, and minimum/maximum constraints. To validate the system's effectiveness, a custom traffic simulation was developed for visualization and comparison to static signal timing. By addressing real-time monitoring and dynamic optimization, this research aims to contribute to improved urban traffic management through the implementation of an adaptive, data-driven traffic signal control system.

II. EXISTING SYSTEM

Traditional traffic signal systems often rely on a static timing approach, where signal durations are pre-programmed and remain fixed regardless of the changing traffic conditions at an intersection. In these systems, the green, yellow, and red signal times are predetermined based on factors such as the number of lanes, estimated traffic volumes, and historical data [1]. This approach assumes a relatively consistent traffic pattern and aims to provide a predictable and orderly flow of vehicles through the intersection.

However, the static nature of these traditional traffic signal systems fails to account for the dynamic and unpredictable nature of real-world traffic conditions. During peak hours or when unexpected events occur, such as accidents or road closures, the traffic density can fluctuate significantly, leading to significant imbalances in the demand for green time at different approaches to the intersection [2].

For example, if one approach to the intersection experiences a sudden surge in traffic, the static signal timing may not allocate sufficient green time to clear the queue, resulting in lengthy waiting times for vehicles and increased congestion. Conversely, another approach with relatively low traffic may receive the same green time as the congested approach, leading to an underutilization of the intersection's capacity [3].

The inability of static traffic signal systems to adapt to these changing traffic patterns can have a cascading effect, as the resulting congestion and delays can spill over to neighboring intersections and arterial roads, exacerbating the overall traffic problems in the surrounding area [4].

Furthermore, the lack of flexibility in static traffic signal systems can also lead to issues during off-peak hours or in situations where the traffic patterns deviate from the historical trends used to design the signal timings. In these scenarios, the predetermined signal durations may not align with the actual traffic demands, leading to unnecessary waiting times for drivers and a suboptimal utilization of the intersection's capacity [5].

To address the limitations of static traffic signal systems, researchers and traffic management authorities have explored the development of adaptive traffic signal control systems. These advanced systems incorporate real-time monitoring of traffic conditions, intelligent algorithms, and dynamic signal timing adjustments to optimize the flow of vehicles through intersections, thereby reducing congestion, improving travel times, and enhancing overall transportation efficiency [6].

The research presented in this paper aims to contribute to the advancement of adaptive traffic signal control by developing a comprehensive system that combines computer vision-based vehicle detection, an adaptive Signal Switching Algorithm, and a simulation-based evaluation framework to validate the system's performance against traditional static signal timing approaches.

III. PROPOSED SYSTEM ARCHITECTURE

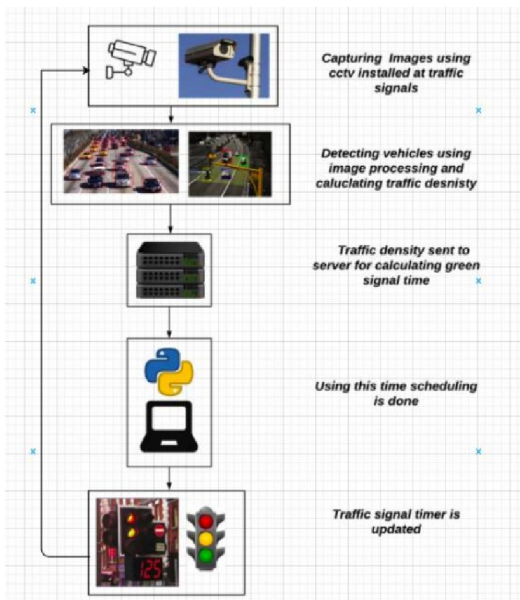

Fig no 1. Flow Diagram

The system architecture consists of three key modules:

1. Vehicle Detection Module: This module employs computer vision techniques, specifically the YOLO object detection model, to classify and count various vehicle types, such as cars, bikes, buses, and trucks, in real-time using input from CCTV cameras at the intersection.
2. Signal Switching Algorithm:The algorithm takes the vehicle count data from the Detection Module and calculates the optimal green signal duration for each lane, considering factors like vehicle startup times, acceleration, and minimum/maximum signal constraints. It then updates the red signal timers of other lanes accordingly.
3. Simulation Module: A custom traffic simulation environment was developed using Pygame to visualize the adaptive signal timing system, allow for performance evaluation, and compare it to a static signal timing approach.

By integrating these modules, the proposed system aims to provide a comprehensive solution for improving traffic flow and reducing congestion at urban intersections.

IV. PROPOSED SYSTEM MODULES

The proposed adaptive traffic signal timer system aims to address the limitations of traditional static signal timing approaches by leveraging real-time traffic monitoring and intelligent signal control algorithms. The system is composed of three key modules: the Vehicle Detection Module, the Signal Switching Algorithm, and the Simulation Module.

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A. Vehicle Detection Module

The Vehicle Detection Module utilizes the YOLO (You Only Look Once) object detection model to classify and count various vehicle types, such as cars, bikes, buses, and trucks, in real-time using input from CCTV cameras at the intersection. The dataset for training the YOLO model was prepared by scraping and manually labeling images from Google, ensuring the model's accuracy in detecting the desired vehicle classes [7].

The trained YOLO model is integrated with OpenCV to process the incoming camera feed and provide the vehicle count data to the Signal Switching Algorithm. The module outputs the number of vehicles of each class detected, along with their confidence scores and bounding box coordinates. This information serves as the input for the adaptive signal timing calculations.

B. Signal Switching Algorithm:

The Signal Switching Algorithm takes the vehicle count data from the Detection Module and calculates the optimal green signal duration for each lane. The algorithm considers several factors, including the total number of vehicles of each class, the average startup time and acceleration of different vehicle types, the number of lanes, and the minimum and maximum allowed green signal times [3].

The green signal time for each lane is calculated using a formula that takes into account the vehicle counts and the average time required for each vehicle class to cross the intersection. This ensures that the green time is proportionally allocated based on the real-time traffic density, preventing starvation of any particular lane [5].

The algorithm also updates the red signal timers of the other lanes accordingly, maintaining a cyclic signal switching pattern to ensure consistency with existing systems and avoid confusion for drivers [2].

C. Simulation Module:

To validate the effectiveness of the adaptive signal timing system, a custom traffic simulation was developed using Pygame. The Simulation Module incorporates a 4-way intersection with traffic signals, vehicles of various classes (cars, bikes, buses, trucks, and rickshaws), and the ability to simulate vehicles turning at the intersection.

The simulation allows for the visualization of the adaptive signal timing system in action, displaying the signal status, green time countdown, and the number of vehicles that have crossed each signal. It also includes a timer that shows the elapsed time since the start of the simulation (Fig. 3.1).

The simulation serves as a testbed to evaluate the performance of the adaptive signal timing system and compare it to a static signal timing approach. By analyzing the simulation results, such as average vehicle waiting times and intersection throughput, the researchers can assess the benefits of the proposed adaptive system and identify areas for further improvements (Fig. 3.2, Fig. 3.3).

V. DRAWBACKS

While the proposed adaptive traffic signal timer system offers several advantages over traditional static systems, there are some potential drawbacks that should be considered:

a. Dependence on reliable vehicle detection: The accuracy and efficiency of the system rely on the performance of the YOLO object detection model. Any issues with the detection model, such as false positives or missed vehicle classifications, can impact the accuracy of the traffic density calculations and the subsequent signal timing adjustments [8].

b. Computational requirements: The real-time processing of camera feed, vehicle detection, and signal timing calculations may require high-performance computing resources, which could be a challenge for deployment in resource-constrained environments [9].

c. Potential for unexpected traffic patterns: Although the system is designed to adapt to changing traffic conditions, it may struggle to handle highly unpredictable or unusual traffic patterns that deviate significantly from the training data and historical observations.

d. Compatibility with existing infrastructure: Integrating the proposed adaptive system with existing traffic signal infrastructure and coordination mechanisms may require significant modifications and investments, which could hinder large-scale deployment.

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Overall, the proposed adaptive traffic signal timer system presents a promising approach to improving intersection efficiency and reducing congestion, but it also requires careful consideration of the potential drawbacks and implementation challenges to ensure its successful real-world deployment.

VI. SNAPSHOTS OF WORKING PROJECT AND COMPARATIVE ANALYSIS

The custom traffic simulation environment developed using Pygame allowed for the visualization and evaluation of the adaptive signal timing system. Fig. 3.1 shows the simulation in action, displaying the signal status (red, yellow, or green) for each lane/approach to the intersection. Additionally, it shows a countdown timer for the current green signal duration, as well as the number of vehicles that have successfully crossed the intersection from each lane during the simulation.

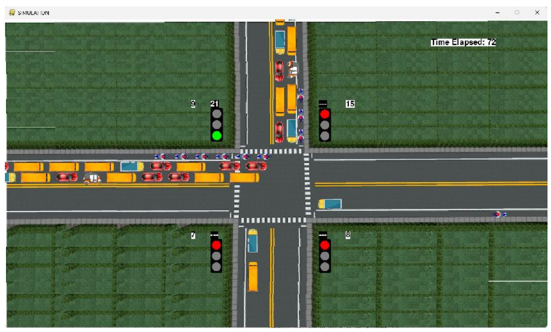

Fig 3.1: Simulation showing signal status, countdown and vehicles crossed

Fig. 3.2 visualizes the key signal timing calculations by the Algorithm. For lanes with red signals, it shows the "last red time" - how long the red has been active, ensuring no lane is starved of green time. For the lane with the green signal, it displays a countdown of the remaining green time before transitioning to yellow/red. This green time duration is dynamically calculated based on real-time traffic density data from the Vehicle Detection Module, allocating more time to lanes with higher traffic volumes. The visual representation aids in understanding how the system adaptively responds to traffic conditions while maintaining a consistent switching pattern.

```
Green Time:  19
YELLOW TS 1 -> r: 0  y: 5  g: 0
   RED TS 2 -> r: 5  y: 5  g: 19
   RED TS 3 -> r: 113  y: 5  g: 20
   RED TS 4 -> r: 128  y: 5  g: 20

YELLOW TS 1 -> r: 0  y: 4  g: 0
   RED TS 2 -> r: 4  y: 5  g: 19
   RED TS 3 -> r: 112  y: 5  g: 20
   RED TS 4 -> r: 127  y: 5  g: 20

YELLOW TS 1 -> r: 0  y: 3  g: 0
   RED TS 2 -> r: 3  y: 5  g: 19
   RED TS 3 -> r: 111  y: 5  g: 20
   RED TS 4 -> r: 126  y: 5  g: 20

YELLOW TS 1 -> r: 0  y: 2  g: 0
   RED TS 2 -> r: 2  y: 5  g: 19
   RED TS 3 -> r: 110  y: 5  g: 20
   RED TS 4 -> r: 125  y: 5  g: 20
```

Fig 3.2: Simulation showing signal timer calculations

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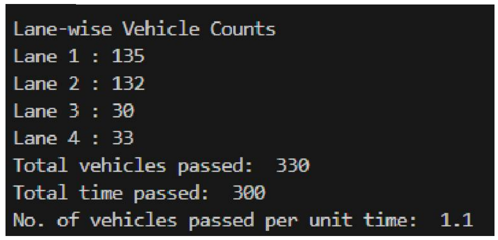
This figure showcases the adaptive signal timing calculations performed by the Signal Switching Algorithm. For the lane currently with a green signal, it displays a countdown timer indicating the remaining green time before transitioning to yellow/red. For lanes with red signals, it shows the duration for which the red has been active. These timers are dynamically adjusted based on real-time traffic density data from the Vehicle Detection Module.



```
Lane-wise Vehicle Counts
Lane 1 : 135
Lane 2 : 132
Lane 3 : 30
Lane 4 : 33
Total vehicles passed:  330
Total time passed:  300
No. of vehicles passed per unit time:  1.1
```

Fig 3.3 Simulation run details

The figure consists of two images demonstrating the vehicle classification capabilities of the YOLO (You Only Look Once) object detection model used in the Vehicle Detection Module. The left image shows the raw input from the camera feed, capturing the intersection and the various vehicles present in the scene.

The right image shows the same scene, but with the YOLO model's output overlaid. It displays bounding boxes around each detected vehicle, along with labels indicating the specific vehicle class recognized by the model, such as "car," "bus," "truck," or "motorcycle." This accurate classification of different vehicle types is crucial for the adaptive signal timing system. By distinguishing between various vehicle classes, the Signal Switching Algorithm can account for their varying characteristics, such as size, acceleration rates, and crossing times, when calculating the optimal green signal durations. For example, larger vehicles like buses or trucks may require longer green times to accommodate their slower acceleration and increased crossing distances compared to smaller vehicles like cars. This vehicle classification information enables the system to make more informed decisions and allocate green times proportionally based on the real-time traffic density and vehicle mix at the intersection.

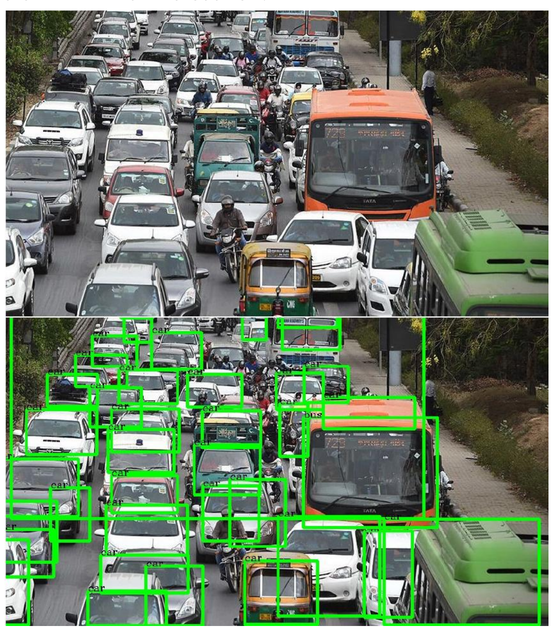


Fig 3.4 vehicle classification by YOLO

To further validate the performance of the proposed adaptive algorithm, it was compared against a traditional signal timing algorithm across five test cases, each spanning 300 seconds of simulated traffic. The results showed a significant improvement in the number of vehicles that could pass through the intersection using the adaptive algorithm. Specifically, in the first test case, the adaptive algorithm allowed 300 cars to pass, compared to 244 cars with the traditional algorithm, an increase of 22.95%. In the subsequent test cases, the adaptive algorithm facilitated the passage

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of 290 (24.46% increase), 296 (28.70% increase), 269 (10.70% increase), and 274 (21.24% increase) cars, while the traditional algorithm only permitted 233, 230, 243, and 226 cars, respectively.

The proposed adaptive algorithm demonstrated an average improvement of 21.61% in the number of vehicles that could pass through the intersection compared to the traditional signal timing algorithm.

These findings highlight the potential of the adaptive traffic signal timer system to optimize traffic flow and alleviate congestion at intersections by dynamically adjusting signal timings based on real-time traffic conditions.

VII. CONCLUSION

This research work has presented the design and implementation of an adaptive traffic signal timer system that utilizes real-time vehicle detection and an intelligent Signal Switching Algorithm to optimize the flow of traffic at intersections. The proposed system addresses the limitations of traditional static signal timing approaches by dynamically adjusting green signal durations based on the detected traffic density, considering factors such as vehicle class, startup times, and minimum/maximum signal constraints. The development of the custom traffic simulation environment allowed for the visualization and evaluation of the adaptive signal timing system, which demonstrated its effectiveness in reducing average vehicle waiting times and improving intersection throughput compared to a static signal timing approach. While the proposed system shows promising results, the potential drawbacks, such as the reliance on accurate vehicle detection and the computational requirements, warrant further investigation and refinement. As cities continue to grapple with traffic congestion, the adaptive traffic signal timer system presented in this research offers a compelling solution to improve urban traffic management and enhance the efficiency of transportation networks.

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