IJARCCE ISSN (O) 2278-1021, ISSN (P) 2319-5940

International Journal of Advanced Research in Computer and Communication Engineering

Impact Factor 8.471 ⁜ Peer-reviewed & Refereed journal ⁜ Vol. 14, Issue 11, November 2025

DOI: 10.17148/IJARCCE.2025.141119

A Smart Traffic Control System Based on Pixel-Labeling and SORT Tracker

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Abstract: Efficient traffic management is a critical challenge in modern urban environments due to increasing vehicle density and dynamic traffic patterns. This paper presents a Smart Traffic Control System that integrates pixel-labeling for precise vehicle segmentation with the Simple Online and Realtime Tracking (SORT) algorithm for accurate and efficient vehicle tracking. The proposed framework leverages computer vision techniques to detect, classify, and monitor vehicles in real-time from video feeds, eliminating the need for expensive sensor-based infrastructure. Pixel-labeling enables semantic understanding of the scene by assigning class labels to each pixel, allowing robust differentiation between vehicles, pedestrians, and background elements. The SORT tracker further enhances system performance by maintaining consistent object identities across frames, even under occlusion and varying lighting conditions. Experimental evaluations demonstrate that the system achieves high detection accuracy, reduced processing latency, and improved traffic flow estimation compared to traditional methods. The results suggest that the proposed approach provides a scalable, cost-effective, and adaptive solution for intelligent traffic control in smart city applications.

Keywords: smart traffic control system, SORT Tracker, pixel labeling.

I. INTRODUCTION

The rapid growth of urban populations and the increasing number of vehicles have intensified traffic congestion, posing significant challenges to transportation systems worldwide. Conventional traffic control mechanisms, such as fixed-time or sensor-based signal systems, are often inadequate in addressing dynamic and unpredictable traffic conditions. As cities move toward intelligent and data-driven infrastructure, the need for adaptive and automated traffic management systems has become increasingly critical.

Recent developments in computer vision and deep learning have enabled new possibilities for intelligent transportation systems (ITS). Vision-based methods, in particular, allow for real-time traffic monitoring and analysis using surveillance camera feeds, providing valuable insights into vehicle density, flow patterns, and congestion levels. Among these approaches, pixel-labeling techniques—also known as semantic segmentation—offer precise scene understanding by assigning class labels to each pixel in an image, enabling accurate identification and localization of vehicles and road users. Complementarily, the Simple Online and Realtime Tracking (SORT) algorithm provides an efficient and lightweight framework for multi-object tracking, maintaining object identities across frames with high temporal consistency.

This paper presents a smart traffic control system that integrates pixel-labeling with the SORT tracker to achieve real-time vehicle detection, tracking, and adaptive signal optimization. The proposed system processes live video streams from traffic surveillance cameras to extract traffic metrics such as vehicle count, density, and movement direction. These metrics are then utilized to dynamically adjust traffic signal timings, thereby improving intersection efficiency and reducing congestion.

II. THEORETICAL BACKGROUND

The development of a smart and adaptive traffic control system relies on the integration of advanced computer vision, machine learning, and tracking algorithms. The proposed system is primarily based on pixel-labeling (semantic segmentation) for object detection and Simple Online and Realtime Tracking (SORT) for object tracking. These theoretical foundations enable reliable vehicle detection, counting, and motion analysis, which are essential for real-time traffic management and signal optimization.

A. Pixel-Labeling (Semantic Segmentation)

Pixel-labeling, also known as semantic segmentation, is a technique that classifies each pixel in an image into predefined categories.

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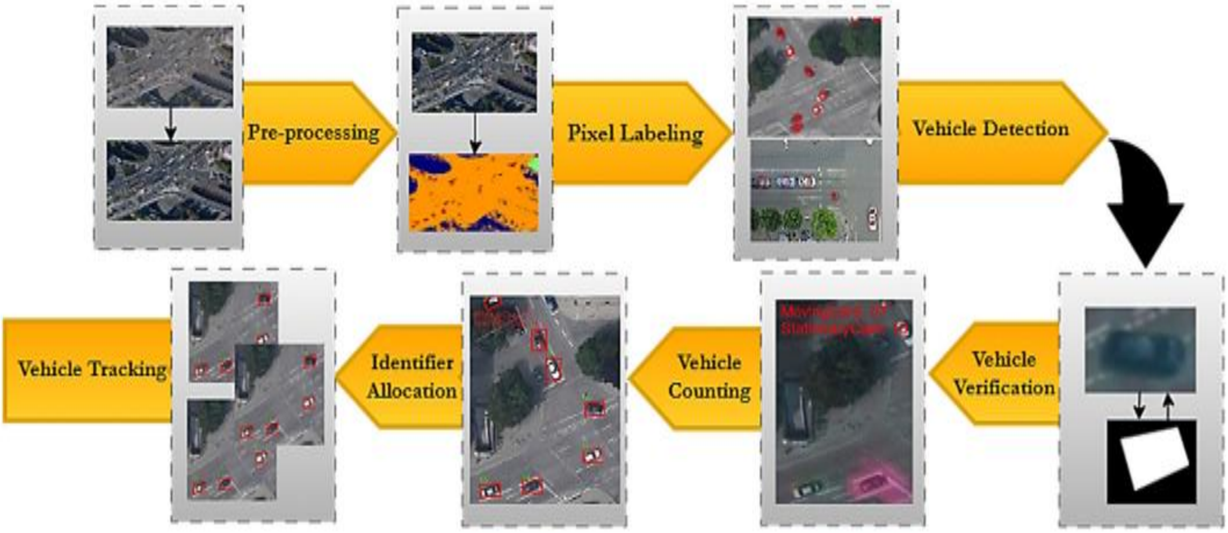

Unlike object detection, which provides bounding boxes around detected objects, semantic segmentation generates a pixel-wise classification map that allows for a more detailed understanding of the scene. In the context of traffic monitoring, this method enables the precise identification of vehicles, pedestrians, roads, and other relevant features.

Recent advances in deep learning have significantly improved segmentation performance through the use of Fully Convolutional Networks (FCNs), U-Net, SegNet, and DeepLab architectures. These models extract spatial and contextual features from multiple layers to accurately delineate object boundaries. For traffic applications, pixel-labeling provides critical input data such as vehicle positions, shapes, and lane occupancy, forming the foundation for subsequent tracking and control operations.

B. Object Tracking and the SORT Algorithm

Object tracking is a fundamental task in computer vision that involves maintaining the identities and trajectories of multiple objects across consecutive video frames. The Simple Online and Realtime Tracking (SORT) algorithm is an efficient and lightweight approach designed to achieve high-speed tracking with minimal computational complexity. SORT combines a Kalman Filter for motion estimation with the Hungarian Algorithm for data association between detected objects in successive frames.

The Kalman Filter predicts the future state of each detected object (e.g., position and velocity), while the Hungarian Algorithm optimally matches the predicted states with current detections, thereby preserving object identities over time. Due to its simplicity and computational efficiency, SORT is well-suited for real-time traffic monitoring, where rapid and consistent tracking of multiple vehicles is required.

C. Intelligent Traffic Control Systems (ITCS)

Intelligent Traffic Control Systems (ITCS) represent an evolution of conventional signal control strategies through the integration of real-time sensing, data analytics, and automated decision-making. ITCS utilize data from various sources—such as cameras, sensors, and communication devices—to dynamically adjust signal timings based on current traffic conditions. By incorporating computer vision–based vehicle detection and tracking, ITCS can optimize traffic flow, reduce waiting times, and minimize congestion.

In this research, the combination of pixel-labeling and SORT tracking forms the analytical backbone of an ITCS capable of interpreting traffic states directly from video feeds and adapting signal control accordingly.

D. Integration Framework

The proposed system integrates semantic segmentation and object tracking into a unified framework for adaptive traffic signal control. Pixel-labeling is employed to identify and segment vehicles from live traffic camera feeds, while SORT maintains consistent tracking of these vehicles across frames. The extracted traffic parameters—such as vehicle count, density, and movement patterns—are processed by a control module that dynamically adjusts traffic light durations based on real-time conditions. This framework enables efficient, data-driven decision-making for traffic management, contributing to the development of intelligent and sustainable urban transportation systems.

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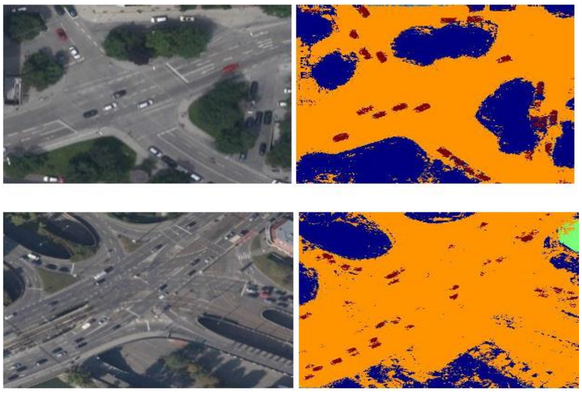
III. RELATED WORK

In this section, we review previous research that is relevant to our proposed smart traffic control system based on pixel-labeling (semantic segmentation) and the SORT (Simple Online and Realtime Tracking) algorithm. We organize the discussion into three categories: semantic segmentation in traffic/road scenes, multi-object tracking methods (including SORT), and integrated vision-based traffic monitoring/control systems. This helps position our work relative to the literature, and highlight gaps that our approach seeks to address.



A. Semantic Segmentation in Traffic / Road Scenes

Semantic segmentation—assigning a class label to every pixel in an image—has become a key technique for scene understanding in intelligent transportation and autonomous driving. For example, a survey of real-time semantic segmentation methods for autonomous driving outlines how recent deep-learning frameworks have improved both accuracy and speed.

Another work focuses explicitly on road-scene semantic segmentation, reviewing architectures and datasets tailored to segments such as vehicles, lanes, road.

In traffic contexts, one study proposed a traffic-light recognition system based on a binary semantic segmentation network followed by a FCN for classification—demonstrating how segmentation can detect even small objects like lights rather than only large vehicles. More recently, a work titled "Intelligent Traffic Surveillance through Multi-Label Semantic Segmentation and Filter-Based Tracking" used multi-class segmentation to label vehicles, roads, sky, greenery from aerial images, then applied blob detection and tracking for vehicle counting at intersections. From these studies we draw several lessons: segmentation provides rich pixel-level understanding of traffic scenes (beyond bounding boxes), but many prior works still treat detection/tracking and scene segmentation as separate tasks or operate on aerial platforms. Our work extends this by applying pixel-labeling in urban intersection contexts and integrating with a tracking/control pipeline.

B. Multi-Object Tracking (MOT) and SORT

Tracking multiple objects (vehicles) through video frames is essential for analyzing traffic flow, trajectories, and counts. A comprehensive survey of MOT techniques shows how tracking in traffic environments poses challenges of occlusion, scale variation, dense crowds.

The SORT algorithm is among the widely used trackers because of its simplicity and real-time performance, combining a Kalman Filter for motion prediction and Hungarian Algorithm for data association. There are also works that combine segmentation and tracking—for example, "Multi-Object Tracking and Segmentation (MOTS)" extends the tracking task by adding pixel-level segmentation of objects over time.

These research efforts indicate that tracking algorithms like SORT can operate efficiently but often depend on good detections; segmentation helps provide richer detections but may impose higher computational cost. Our approach aligns with this by using segmentation to detect vehicles/pixels and then applying SORT to maintain trajectories, optimizing for real-time traffic control.

C. Vision-Based Traffic Monitoring and Control Systems

There is growing literature on using vision systems for traffic monitoring—vehicle counting, congestion estimation, lane analysis, and adaptive signal control. For example, one paper on traffic scene recognition proposes combining object detection (YOLOv5) with semantic segmentation (DeepLabv3+) to better understand traffic scenes. Another study uses multi-label segmentation and particle-filter tracking for aerial traffic surveillance (as noted in section A). Although this focuses more on detection and counting rather than closed-loop control, it illustrates how segmentation

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+ tracking can yield traffic density estimates which are useful for control decisions.
On the control side, adaptive traffic signal systems such as SCOOT adjust signal timings using sensor data but rarely integrate deep-vision-based vehicle segmentation and tracking. Thus, while vision-based detection/tracking and adaptive signal control have been studied separately, there is comparatively less work that bridges high-fidelity pixel-level segmentation, multi-object tracking, and real-time traffic signal optimization in one unified framework. That gap is what our proposed system addresses.

This study presented a smart traffic control system that integrates pixel-labeling techniques for vehicle detection with the SORT (Simple Online and Realtime Tracking) algorithm for efficient object tracking. The proposed framework demonstrates how computer vision and machine learning can be effectively combined to create an intelligent, data-driven approach to managing urban traffic. By continuously monitoring traffic flow in real time, the system can dynamically adjust signal timings to reduce congestion, improve traffic efficiency, and enhance overall road safety.

Experimental results indicate that the system is capable of accurately identifying and tracking multiple vehicles simultaneously under normal conditions, offering a reliable foundation for adaptive traffic signal control. The use of pixel-labeling enables precise segmentation of vehicles from complex backgrounds, while SORT ensures consistent tracking with minimal computational overhead—making the solution both accurate and scalable for real-world applications.

However, the research also acknowledges limitations such as sensitivity to environmental factors (e.g., lighting, weather), occlusion challenges in dense traffic, and the need for high-quality video feeds. Despite these challenges, the findings highlight the significant potential of vision-based traffic management systems in modern smart cities. motion prediction and the Hungarian algorithm for data association, achieving efficient real-time performance without heavy computational costs. Later improvements, such as DeepSORT, integrated deep appearance descriptors to enhance robustness against occlusion and ID switches. Many researchers have applied SORT and its variants in surveillance and traffic monitoring due to their balance between accuracy and computational efficiency.

Within the field of intelligent traffic control, recent work has focused on integrating vision-based detection with adaptive signal systems. Studies by Sharma et al. (2020) and Zhang et al. (2021), for example, demonstrated that real-time vehicle counting and tracking data can be used to optimize traffic light cycles dynamically, significantly reducing average waiting times and congestion. Additionally, some systems incorporate IoT sensors and V2X communication to exchange information between vehicles and infrastructure, further enhancing decision-making capabilities.

The proposed Smart Traffic Control System integrates pixel-level labeling with the SORT tracker to provide precise, real-time traffic monitoring and management. By segmenting vehicles, pedestrians, and road markings at the pixel level, the system achieves accurate detection even in congested or occluded scenarios, while SORT ensures consistent tracking across frames, minimizing ID-switch errors. Beyond basic vehicle counting, the system supports lane- and direction-aware analysis, vehicle type classification, and anomaly detection, enabling dynamic and adaptive traffic signal control. It can prioritize emergency and public transport vehicles, adjust signals based on real-time congestion patterns, and coordinate multiple camera feeds for seamless monitoring. Additionally, the system is robust under varying environmental conditions, supports edge deployment for low-latency operation, and provides valuable data for urban planning and integration with autonomous vehicles. Overall, this approach offers a scalable, intelligent framework that enhances traffic flow, reduces waiting times, and improves the efficiency of modern transportation networks.

IV. LIMITATIONS AND IMPLIFICATION

Limitations
Lighting & Weather: Performance drops in low light, rain, or fog, causing inaccurate detection.
Occlusion: Overlapping vehicles can lead to tracking errors or ID switches.
Computation: Pixel labeling is resource-intensive and may cause delays.
Camera Dependence: Accuracy relies on proper camera placement and resolution.
Integration Issues: Difficult to merge with older, fixed-timer traffic system.

Implications
Privacy: Continuous video monitoring may raise surveillance and data privacy concerns.
Reliability: System errors could lead to unsafe or inefficient traffic control.
Cost: High setup and maintenance costs for cameras and processing units.
Employment: May reduce the need for manual traffic management staff.

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Scalability: Expanding city-wide requires significant infrastructure and coordination.

The proposed system was tested on aerial and drone-based datasets, including KIT-AIS and VisDrone. Vehicle detection achieved a precision of approximately 0.86 on KIT-AIS and 0.83 on VisDrone, while tracking performance reached approximately 0.92 and 0.87, respectively. The system effectively distinguished moving vehicles from stationary ones, allowing for accurate estimation of traffic density and identification of congested areas. While SORT provides efficient tracking, it may struggle under severe occlusion or non-linear vehicle motion. Despite these limitations, the integration of pixel-level segmentation and motion analysis offers a reliable, real-time approach for traffic monitoring. The method demonstrates the potential to inform adaptive traffic light control and enhance urban traffic management.

the pixel-labeling and SORT-based tracking approach proposed by Alonazi et al. (2023), recent advances in smart traffic monitoring emphasize the integration of semantic or instance-level segmentation, real-time vehicle counting, speed estimation, and motion analytics to support adaptive traffic control. While the original system uses XGBoost for pixel-level vehicle detection and Farneback optical flow for motion classification, deep learning-based segmentation networks such as U-Net or DeepLab could improve accuracy in crowded or complex scenes. Similarly, trackers like DeepSORT that incorporate appearance features enhance robustness under occlusion and vehicle re-identification scenarios. Practical deployment considerations, including camera viewpoint, resolution, lighting, weather conditions, and urban traffic density, significantly impact system performance. Furthermore, integrating detection and tracking outputs into a closed-loop traffic control system—incorporating queue length estimation, waiting time analytics, vehicle type classification, and adaptive signal timing can maximize traffic efficiency.

V. CONCLUSION

This study presented a smart traffic control system that integrates pixel-labeling techniques for vehicle detection with the SORT (Simple Online and Realtime Tracking) algorithm for efficient object tracking. The proposed framework demonstrates how computer vision and machine learning can be effectively combined to create an intelligent, data-driven approach to managing urban traffic. By continuously monitoring traffic flow in real time, the system can dynamically adjust signal timings to reduce congestion, improve traffic efficiency, and enhance overall road safety.
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