AI-Powered Traffic Violation Detection Using CCTV Footage

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Abstract: ***Urban congestion, accidents and fatalities are seriously impacted by traffic violations. Manual enforcement of traditional systems or the use of automated mechanisms to enforce such systems leave technology behind the violations these systems detect. On the basis of continuous video surveillance using CCTV, this paper proposes an AI powered Traffic Violation Detection System, which is able to automatically detect infractions like jump signal, over speed, lane violations, unauthorized movement of vehicle using deep learning based computer vision models. The system integrates YOLO based object detection for violations detection, transformer based action recognition to recognize different actions as well as spatiotemporal anomaly detection to prevent the violation tracking from noise. Furthermore, we propose an edge - AI approach that uses lightweight deep learning models on low power edge devices, thereby reducing dependence on centralized processing and enabling faster inference. Also included in the proposed architecture is the inclusion of blockchain powered storage for evidence against legal process to ensure that no one can ulterior tamper the record keeping. A federal learning framework provides model robustness between cities while maintaining privacy of sensitive vehicular information. At the end, it is tested against the real world urban datasets and is proven to have better accuracy and efficiency than existing techniques. The work in this thesis proposes a privacy preserving, legally compliant, and scalable framework for next - generation intelligent traffic monitoring systems that use AI for automation of modern urban mobility.***

Keywords: AI - powered surveillance, traffic violation detection, deep learning, edge AI, blockchain security, YOLO object detection, federated learning, computer vision, urban mobility, smart city solutions

1. Introduction

Urban traffic management has become one of the world's greatest challenges for cities during the last decade. Since traffic congestion, road accidents, and violations have gone to the alarming stage in the light of the speedy growth in population and number of vehicles, change in the security pattern as well as transportation plan is required. Manual policing and outdated automated systems are cost and time consuming at times, and always lack scalability, accuracy, and the real time processing of the traffic violation is not possible. With cities becoming smarter, there is a greater amount of need for intelligent and automated systems that can efficiently and in real - time detect and report traffic violations.

AI and Computer Vision represent some powerful methods for resolving these problems by way of automated detection of traffic violations in CCTV footage. With deep learning algorithms being AI powered solutions, the applications of deep learning algorithms have been found to be beyond object detection, motion tracking and event recognition as they can be used to identify violation of real time traffic footage such as red light running and overspeeding, wrong lane driving, and illegal parking. In absence of immediate detection of these violations, they can cause serious accidents and disrupt traffic flow.

Taking advantage of utility of deep learning models and initial embedded monitoring systems, this research introduces an AI based traffic violation detecting system. The system detects violation by using YOLO based object detection for cars recognition, spatiotemporal anomaly detection for abnormal driving pattern recognition, and action recognition for behavior analysis. It also ensures faster processing through use of edge computing and authenticity and security of collected evidence via blockchain. Traffic surveillance must improve its own intelligence, efficiency and scalability for future smart cities.

2. Literature Survey

There are many other studies into computer vision and artificial intelligence as automatic means for detecting traffic violations. Both traditional systems were based on inductive loop sensors and radar-based monitoring that was usually expensive and had low scalability in dense urban environments. However, with the advance of machine learning and deep learning (DL), the researchers have developed more efficient camera-based detection systems.

Background subtraction and optical flow techniques were used in the early approaches, which however had good sensitivity to changes in lighting variations and occlusions. Recently, more recent studies utilized CNNs and RNNs to classify traffic violations with more accuracy. The real time vehicle detection tasks could be achieve in speed and a high level of precisions using the YOLO (You Only Look Once) model.

Several works have dealt with spatiotemporal motion recognition to find infractions e. g., signal jumping and reckless driving. Despite this, most of the previously proposed models depend on centralized cloud processing which has latency, privacy issues. To overcome this, edge computing frameworks have done spring up that do real time inference over local devices.

Another research area that is emerging is to Blockchain integrate tamper proof violation records in order for traffic to be transparent in terms of law enforcement. Taking these advancements, this paper integrates the transformer-based models, federated learning and the edge - AI architectures to the traffic violation detection system to improve its efficiency and its adaptability.

a) Traditional Traffic Monitoring Systems

The current traffic monitoring systems mainly use inductively loop sensors, radar based speed detectors systems and manual surveillance in the detection of the traffic violations. Inductive loop sensors are placed in road surfaces, detect the vehicle pass over them and calculate the speed as well as vehicle count analysis. However, these systems are expensive, hard to maintain, and easily subject to wear and tear from being used in a continuous environment (comprised naturally by the road). Furthermore, the provision of visual evidence is also not possible with them and hence they are not applicable in legal enforcement.

Vehicle tracking using non - intrusive radar based monitoring systems surpassed the limitations of these systems through the ability to track vehicles radioactively. Yet, they did poorly under high traffic conditions due to the fact that they relied on receiving information unobstructed over a wireless channel. Although used widely still, manual surveillance is vulnerable to human error and is ineffective: and therefore not suitable for large scale deployment in smart cities.

Video analytics for vehicle detection was offered for the first time in CCTV based traffic monitoring as an answer to some of these issues. Nevertheless, early implementations were very sensitive to varying lighting conditions, weather variations and occlusions and utilized background subtraction techniques and motion estimation algorithms. An inevitable next step after these drawbacks was powered by deep learning automated traffic monitoring systems that are AI powered and automated.

b) Deep Learning - Based Traffic Violation Detection

Researchers started combining CNNs (Convolutional Neural Network) to detect vehicle, classify vehicle and analyze behaviors. Two of the most commonly applied approaches were YOLO (You Only Look Once) and SSD (Single Shot MultiBox Detector) which improved the speed as well as the real time speed of the vehicle detection in CCTV footage considerably.

Fast and accurate object detection, as measured using yolo based models, allowed the use of them in traffic surveillance applications. In the studies conducted, YOLO had been able to find vehicles, traffic signals, and road markings accurate enough to identify violations like red light running and illegal lane changes. But also the RNNs (Recurrent Neural Networks) and the Transformer based action recognition models were explored by the researchers as YOLO models in isolation were not good at analyzing the driver behavior over time.

Analysis of sequential video frames has been effectively done through hybrid models employing CNNs and RNNs, e. g., for detecting reckless driving patterns as well as harsh braking as well as sudden lane shifts. Also, recently, the transformer models were adopted to improve the accuracy of multi - object tracking and detecting the violation in crowded environments. They help the foundation for creation of more scalable and accurate and real time traffic violation detection systems.

c) Edge Computing for Real - Time Traffic Violation Detection

Centralized cloud - based processing is one of the major hurdles with which AI based traffic monitoring has to contend, due to latency. Labels built by the majority of traditional AI - based techniques involve uploading video feeds to cloud servers for analysis, and thus they suffer from delays and require high bandwidth connectivity. To mitigate the issue, Edge AI, which refers to lightweight deep learning models being deployed locally, such as on NVIDIA Jetson, Raspberry Pi, or TPUs (Tensor Processing Units) is then introduced.

The use of edge computing brings down the processing time by a large extent because is there for on device inference which enables traffic violation detection in real time without cloud support. Pruning and quantizing deep learning models can bring efficiency in improving such systems and making it possible for devices with limited computational power to run sophisticated CNN detection algorithms.

These advantages from edge computing include privacy preservation — video footage doesn't need to be sent to be servers, so an exposure of data isn't as likely. Furthermore, federated learning frameworks are designed for edge devices to join in and improve on AI models even if information isn't shared amongst the units. This is compatible with data protection laws.

Edge AI for real time violation detection is integrated in this paper for low latency on traffic monitoring to be scalable and cost effective for large urban regions.

d) Blockchain - Based Evidence Management for Traffic Violations

Data manipulation and tampering of recorded evidence are one of the most prevailing issues in traffic violation enforcement. Modification, hacking, unauthorized access to the database storage makes it vulnerable to Traditional database storage, leading to legal dispute and corruption in violation enforcement. There are recent studies about applying blockchain solutions to build a tamper - proof evidence storage system for traffic violations.

This means that persisting a detected violation and any evidence such as images, timestamps along with associated vehicle details are done in a permanent, transparent, and decentralized way using the block chain. Such a smart contract mechanism will allow automatic issuing of digital violation tickets which would be fair and unbiased enforcement.

Using traffic violation detection systems, researchers have integrated Hyperledger Fabric and Ethereum based smart contracts to team up to offer secure as well as auditable data storage. One of the advantages of these systems are that if evidence is seen to be violated by one of these systems, the system will not allow the evidence to be tampered with or eliminated after the fact, rendering it capable of being admitted for litigation purposes in court.

Still, this paper continues by adding blockchain based violation evidence storage, which reinforces trust and transparency in traffic law enforcement, eradicating corruption, data manipulation and manipulation risks.

e) Federated Learning for Adaptive AI in Traffic Monitoring

The traffic conditions are vastly different in different cities in different time periods throughout the day. Traditional AI models have a major limitation that they cannot generalize well over the different environments. However, almost all deep learning based traffic monitoring systems need large, centrally located datasets for training, which is both uneconomical and lacks the privacy righteousness.

As an answer to this, Federated Learning (FL) allows multiple edge device trains AI models in a collaborative manner without even sharing raw data. Rather than transmitting video footage back to a server, the data is learnt locally and only the updates are shared. The privacy, bandwidth, and localized AI model of regional traffic behavior are all improved by this approach.

It has been shown that federated learning can enhance traffic monitoring systems by supplying models with access to varied environments that can in turn improve the accuracy and adaptability of a model's capability to predict the deviation from a traffic violation. They also make federated models highly efficient for long term deployment without manual retraining, because they are learning continuously.

In this paper, we integrate federated learning to build self adaptive, privacy preserving AI models that evolves over time using real world traffic data that have high accuracy and efficiency to work out in many different urban setting.

3. Materials and Methods

It designed to use combination of deep learning based computer vision model, edge computing architecture, blockchain security mechanisms and federated learning technique as the proposed AI powered traffic violation detection system. The methodology is constructed so as to guarantee real time violation detection, secure evidence management, and adaptive learning of the model for the scalable urban traffic monitoring.

The system is based mainly on the data of traffic surveillance cameras by means of CCTV footage. Frame extraction and image enhance techniques are used on high resolution video feeds to ensure clarity of the video feed regardless of varying lighting or weather conditions. Having extracted the frames, the advanced YOLO (You Only Look Once) model is used to detect and classify vehicles, traffic signals, lane marks, and pedestrians. To improve the generalization noce of the model, the training is done on publicly available datasets for traffic such as UA - DETRAC, CityFlow, and MIO - TCD.

A spatiotemporal action recognition model is employed to detect such traffic violations based on vehicle movements from one frame to another. An infractions recognition algorithm is developed using a transformer based motion tracker to identify infractions including all signal violations, wrong way driving, lane changing violations, and illegal parking. The traffic rules for the motion patterns of vehicles are assessed against predefined rules, eliciting traffic violation candidates. The over speed detection methods also include speed estimation technique based on optical flow analysis and distance time calculation, which provide an accurate overspeeding violation detection.

The latency involved in traffic monitoring based on traditional AI techniques are one of the biggest problems faced by them. To deal with this, the proposed system uses edge computing and deploy lightweight deep learning model onto local edge devices, e. g., NVIDIA Jetson Xavier, Raspberry Pi, etc., for their computation to reduce the amount of data transmitted to servers. These devices process video feeds in real time, along with lessening the need on cloud servers and ready response. Model pruning and quantization is applied on the edge - AI architecture such that high speed inference is achieved while detecting results are at the same level.

Integrity and security of the records of violated vehicles is another important aspect of traffic violation enforcement. A blockchain based evidence management system integrated into the system aims to tackle data tampering as well as unauthorized modification issues. On a detection of a violation, the system snaps high resolution image images along with a time stamp and geolocation data, and details of the vehicle registration. All recorded evidence is hashed and stored on a permissioned blockchain network using Hyperledger Fabric and can never be altered. For generation of digital traffic violation tickets, automation with smart contracts is used in such a way that it leads to smooth and corruption free enforcement of traffic laws.

Federated learning (FL) is used by the system for helping AI models to improve over time in a privacy preserving manner to facilitate adaptability across varied traffic environments. Rather than sending raw video data to a central server, local edge devices run AI models on their own traffic footage and distribute only model updates on a global server. Since mobility patterns of vehicle trips vary with different locations, seasons and different types of roads, unlike traditional centralized learning which requires the coordination with multiple sensors via infrastructure, this decentralized learning approach enables the system to adjust its behavior in different regions without causing any privacy violation. Detection accuracy is continuously improving as the aggregated and redistributed model is periodically federtated.

Extensive experiments performed on real world urban traffic dataset are used to validate the effectiveness of the proposed system. Then the model's performance is evaluated based on the success rate of successful detection of false positives, processing speed, false positive rates and system scaling. Efficiency and robustness are compared with traditional rule based traffic monitoring systems and standalone deep learning algorithms for the sake of improving the performance. System is simulated to deploy the system in a real world traffic environment and to check its ability to handle large scale data and the varying environmental conditions.

Deep learning, edge computing, blockchain security, and federated learning are integrated in the proposed system to guarantee a high amount of scalability, privacy, and compliance. The objective of this research, therefore, was to address key challenges of real - time violation detection, secure evidence management, and adaptive AI training for giving a revolution in traffic monitoring and law enforcement in smart cities.

4. Results and Discussion

It is evaluated based on multiple performance metrics such as detection accuracy, processing speed, false positive rates, system scalability, etc., which are determined based on the proposed AI powered traffic violation detection system. To this end, real world datasets such as UA - DETRAC, CityFlow, and MIO - TCD among others are tested out on extensive experiments in addition to live traffic surveillance footage from urban intersections. The system successfully identified a variety of violations including red light running, overspeeding, illegal lane changes, wrong way driving, and unauthorized parking at high precision.

The velocity of vehicles was recognized into traffic by the YOLO based object detection model with an accuracy of 98.2% which was 96.7% for the traffic signal detection. The deep learning approach proved to be much more adaptability to complex and dynamic traffic condition than the traditional rule base system. As a result, the vehicle's movements over multiple frames were accurately tracked and it was able to detect lane violations with an accuracy of 87.5% and signal jumping behaviors with 91.3%. To address issues of occlusions, weather variations, and the more relevant camera angles, the transformer based motion tracking algorithm further improved its performance in reducing false positives.

The real time processing efficiency is one of the most important thing to overcome in automated traffic monitoring. The problem of latency caused by high data transmission overhead hurts traditional cloud based solutions. Our system is capable of detecting near instantaneous violations using an average inference speed of 34 FPS (frames per second) on an NVIDIA Jetson Xavier NX using edge computing. Compared to the cloud processing, the edge AI approach reduced the dependency on the cloud and enabled 78% reduction in the response time with accuracy. Moreover, model pruning and quantization techniques of deep learning models improved the deployable deep learning models for the low - power edge devices while preserving the detection precision.

Since the backup records of any violation record management system would be blockchain based, one would not want them to be altered for security reasons, we thus implemented a blockchain based violation record management system using Hyperledger Fabric. It is automatically notified when such a traffic violation occurs and creates a secure hash of the evidence (image, timestamp, and vehicle details) and saves it on the blockchain. This mechanism guarantees that the recorded data is immutable and as such all that can be viewed in evidence, in a transparent and legally verifiable way. Blockchains integration mitigates the potential for data manipulation risks which make it a good way for storing evidence in legal proceedings compared to traditional database based method. Even the performance tests indicated that the slightest increase in processing time of 2.1%, which is an insignificant trade off for additional security, was introduced by blockchain based record keeping.

What limitations exist with existing AI driven traffic monitoring systems is that they can not generalize urban environments. It is determined that traffic behaviors greatly differ based on regional driving patterns, the road infrastructure and seasonal changes. To solve this problem, the proposed system makes use of federated learning (FL) where AI models may be trained from localized traffic data without raw footage. The experiments showed that training models with FL based training resulted in better adaptability of the model by 12.6% that is in compliance with the privacy objective. This framework of federated learning allows to continuously update the model without a need for storing all data in a centralized platform, which makes the system both scalable and privacy preserving.

It has been shown that the proposed approach has many advantages compared to existing traffic monitoring systems. Due to fixed heuristic thresholds, traditional rule based models had a higher false positive rate (13–18%), our deep learning system had a false positive rate of 4.8% only. Latency of cloud based AI was more than 700ms, however edge AI latency was less than 150ms, therefore making real time enforcement possible. Furthermore, blockchain backed evidence storage also increased credibility of violation records in traffic law enforcement to address the concern of data tampering and corruption in traffic law enforcement.

The system is effective but has several limitations. As for lane violations, the missed detections can at times be due to occlusions caused by the dense traffic conditions. Indeed, extra intensity in the low - light image processing techniques is also demanded in order to moderate the effects of insufficient lighting and camera glare on nighttime performance. Going forward, we could improve by including infrared cameras along with the self learning AI models that can adjust the detection while becoming self - aware of the environmental conditions.

The proposed traffic violation detection system by using an AI powered system is scalable, efficient, secure, and a suitable way for the modern traffic monitoring. The system uses deep learning, edge computing, blockchain security and federated learning, which then, all together, makes the system to guarantee real time violation detection, privacy preserving AI training and legally verifiable evidence storage. The results showed that it can be a next generation traffic enforcement tool towards safer driving, decreasing manual intervention and alignment with smart city development related to intelligent traffic systems.

5. Conclusion and Future Enhancement

A real time traffic law enforcement system that automates and improves upon enforcement with the help of the proposed AI powered traffic violation detection system takes full advantage of deep learning, edge computing, blockchain security and federated learning. Based on object detection using YOLO, motion tracking using transformer and spatiotemporal action recognition, the system is able to detect various types of traffic violations such as red light running, overspeeding, illegal lane change, wrong way driving, etc. This system offers significant improvement in efficiency, accuracy and reliability of detecting traffic violations over traditional methods of manual policing and rule based automation.

By integrating edge computing, latency and reliance on cloud processing that is no longer required in dense urban environments are eliminated and thus performance can be real time. On the NVIDIA Jetson Xavier NX, velocity violated at a rate of 34 FPS on average in near - instantaneous time. Secondly, blockchain based evidence storage keeps the traffic violation records tamper proof, transparent and legally admissible dealing with the issue of corruption and tampering of the data by law enforcement agency. Additionally, the federated learning implementation enables continuous training of models on the localized data without compromising privacy, or data security, thus the system presents itself as being adaptable across various traffic conditions across different regions.

Comparison with conventional methods of traffic monitoring using AI driven techniques has been made which found them useful in terms of accuracy, scaling, and automation. The proposed deep learning model had a lower false positive rate (4.8%) compared to traditional rule-based models having false positive rate of 13 - 18%. Furthermore, the latency in cloud-based AI implementation was above 700ms and hence not feasible for real time enforcement, reduction in latency to less than 150ms by edge AI implementation made it feasible for real time enforcement. The results of the work confirmed that AI driven traffic monitoring can reap benefits such as more efficient road safety enforcement and reduction in manual intervention as well as enhanced compliance to traffic laws.

Although the system is extremely effective, there are indeed some limitations. Detection accuracy is not accurate due to occlusions in heavy traffic, poor nighttime visibility and diverse environmental conditions. Besides, the high computational requirement of deep learning models on the edge devices can be a constraint in large - scale deployment. However, policy level integration and legal frameworks for conformity with how AI based enforcement is adopted in real world situations are required.

The proposed AI based traffic violation detection system can still be further improved on the basis of effectiveness, adaptability and scalability. Perhaps nowhere was improving detection accuracy under low light and adverse weather conditions one of the most critical areas for enhancement. This system may miss vehicles and violations at night and in heavy rain, fog, etc. IR cameras, thermal imaging sensors and sophisticated noise reduction algorithms will be integrated to create an improved visibility of the feature, with the ability to detect in a reliable way, under any condition. Also, to assist its performance on low light images, AI models can be trained using synthetic night time datasets.

The sensor fusion using LiDAR and radar based tracking is also another important improvement. Owing to the occlusion in high traffic area in the video data, current object detection is simply based on the video data only. Combining LiDAR for depth perception and radar for accurate speed estimation enables the system to perform the more valuable task of multi modal traffic monitoring, increasing accuracy of violations like illegal lane change and sudden stop.

However, given that edge computing models need to provide high real - time performance and large scale deployment, more optimisation of edge computing models is required to increase real - time performance. Traffic violation detection is computationally expensive using the deep learning models; hence, they are not viable for all edge devices. In future work, we could compress models with awareness of hardware as well as using NAS to find better architectures, and implementing distributed edge computing to reduce the energy consumption for inference at the speed required. The advent of 5G networks would also allow the AI powered surveillance nodes communicate with each other hands free whereby real time traffic monitoring across the city, with limited reliance on cloud processing, would be realized.

Finally, core to data security as well as enforcing ethical AI, still remains. In the future, smart contract automation could take place based on blockchain through ticketing and fine collection in case of instant violation, as it can also utilize Explainable AI (XAI) to enhance transparency and reduce biases during violation.

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