Enhancing Urban Traffic Efficiency Through Traffic Flow Prediction using Long Short-Term Memory Neural Networks

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□ ABSTRACT □

Traffic congestion is a widespread issue affecting urban areas worldwide, leading to significant economic and environmental costs. Predicting traffic flow accurately is crucial for effective traffic management and planning. This study aims to develop a robust traffic flow prediction model that leverages the capabilities of Long Short-Term Memory (LSTM) neural networks in handling time series data. Suggested models were trained and tested on a comprehensive dataset, which included various traffic parameters provided by The Luxembourg administration of Ponts et Chaussées. The models achieved high accuracy in forecasting the average speed and flow rate in a studied location. So, the outputs can be used in an assistance system to help humane operators adjust traffic signal timings based on the predicted traffic conditions, reducing congestion and improving flow.

Keywords: Traffic Flow Prediction, LSTM neural networks, Deep Learning, Urban Traffic Management.

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تعزيز كفاءة حركة المرور في المناطق الحضرية من خلال التنبؤ بالتدفق المروري باستخدام شبكات الذاكرة الطويلة قصيرة الأمد

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☐ ملخّص ☐

يُعد الازدحام المروري مشكلة منتشرة تؤثر على المناطق الحضرية في جميع أنحاء العالم، وتؤدي إلى خسائر اقتصادية ومشكلات بيئية كبيرة. يؤدي التنبؤ الدقيق بتدفق حركة المرور دوراً هاماً في إدارة المرور على الطرق العامة بشكل فعّال. تهدف هذه الدراسة إلى تطوير نموذج للتنبؤ بتدفق حركة المرور بالاستفادة من قدرات شبكات الذاكرة الطويلة قصيرة الأمد (LSTM) على التعامل مع بيانات السلاسل الزمنية. تم تدريب النماذج المقترحة في هذا البحث واختبارها على مجموعة بيانات معيارية تتضمن ميزات متعددة للحركة المرورية في مدينة لوكسمبورغ. وقد حققت النماذج دقة عالية في التنبؤ بمتوسط السرعة ومعدل التدفق في الموقع المدروس. وبالتالي، يمكن استخدام مخرجات تلك النماذج ضمن نظام دعم قرار يساعد المشغلين البشريين في عملية ضبط توقيت إشارات المرور بناءً على الحالة المرورية المتوقعة، مما يقلل من الازدحام ويحسن التدفق المروري.

الكلمات المفتاحية: التنبؤ بتدفق حركة المرور، شبكات الذاكرة الطويلة قصيرة الأمد، التعلم العميق، إدارة حركة المرور في المناطق الحضرية.

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Introduction:

The rapid growth of urbanization and the increasing number of vehicles on the roads has led to a significant increase in traffic congestion in cities and lead to increased fuel consumption, especially capitals and large cities, all over the world. Congestion in transportation refers to the situation where there are more vehicles on the road than usual, leading to slower speeds of vehicles within a specific time frame [1]. Traffic congestion leads to wasted time and increased travel costs for passengers and also contributes to environmental pollution and decreased overall quality of life.

Deep Learning (DL) can be used to improve traffic flow by predicting passenger flow within a city, accurately capturing real flow structures, and simulating traffic flows in different scenarios related to city development [2]. It can also assist in traffic management by predicting traffic flow at different time intervals, such as hourly, daily, weekly, or yearly [3]. Overall, Deep Learning offers promising approaches for accurately predicting and managing traffic flow, contributing to more efficient transportation systems.

Traffic control is a challenging task in metropolitan areas. To reduce the expenses related to traffic congestion, many countries around the world have implemented Intelligent Transportation Systems (ITS) [4].

The Traffic Flow Prediction (TFP) problem is a temporal data forecasting problem that involves predicting traffic flow on urban roads at a future time by using historical data gathered from one or more locations in previous periods.

This study's objective is to forecast TF in an urban city utilizing Machine Learning (ML) techniques.

Research Importance and Objectives:

- To develop and evaluate Long Short-Term Memory (LSTM) models that can predict traffic speed and flow rate to detect congestion.
- To assist policymakers, transportation agencies, and urban planners in the implementation of traffic management systems that utilize deep learning, providing them with recommendations and insights

1- Related work

In this section, an all-inclusive examination of the literature pertaining to the optimization of traffic flow, the implementation of deep learning (DL) techniques in transportation, and the fusion of these methods to augment the efficiency of traffic flow is presented.

The ANN model presented by Kumar et al. in [6] considers factors like traffic volume, speed, density and day of the week, using past traffic data. The findings show that when the time interval is increased from 5 minutes to 15 minutes for collecting TF data, the ANN performs consistently and provides good results by treating speeds of different types of vehicles separately as input variables.

In their research, Wu, Y., et al. [7] trained a Deep Neural Network (DNN) on large amount of data to predict TF. The study introduces DNN-BTF model that uses convolutional neural networks to extract spatial data and recurrent neural networks to extract temporal data from TF. It provides a visual representation of how the DNN-BTF model interprets TF data to disprove the idea that neural networks are "black-box" methods. The proposed DNN-BTF model was tested on traffic prediction with a lengthy time horizon using data from PeMS.

Ma, D. et al. [8] present technique based on Pattern matching prediction. It involves first categorizing past data using clustering algorithms based on similar features. Then convolutional neural networks with long short-term memory (CNNs-LSTM) are trained for each category. When making a prediction for a target day, the model for the group most similar to the target day at each time point is selected based on determining the similarity. The technique is demonstrated to improve prediction accuracy.

Research Tools and Methods:

The methodology's essence involves the build and assessment of deep learning (DL) models. These models are trained on the task of traffic prediction, utilizing techniques such as LSTM. Model performance will be rigorously evaluated using metrics like Mean Square Error (MSE) and Root Mean Square Error (RMSE).

The regulation and control of vehicle movement to ensure safe and efficient transportation is known as traffic management. Various strategies, such as traffic signal timing, lane allocation, and speed limit enforcement, in addition to the use of intelligent transportation systems are employed for this purpose, which gather and share real-time traffic information. Sensors and data analytics are utilized in adaptive traffic management systems to modify traffic signal timings and lane allocations in response to prevailing traffic conditions, with the aim of decreasing congestion and enhancing traffic flow [2].

1-Review of existing traffic management techniques

Here's an overview of some prominent approaches in the domain of traffic management techniques [9, 10, 11]:

- Traffic Lights Control Systems: Current traffic lights operate according to fixed time signals or adapt in real time based on information received from a group of local sensors.
- Traffic Surveillance and Data Collection: Surveillance cameras and other sensors are used distributed on different parts of the roads, which helps in making the right decision and reduces congestion.
- Intelligent Transportation Systems (ITS): Variable Message Signs (VMS) are used along roads to notify drivers of real-time traffic information
- Traffic Flow Optimization Algorithms: Through machine learning algorithms, traffic data from both historical and real-time sources is analyzed to forecast traffic congestion, enhance traffic signal timings, and provide alternative route recommendations. Our research focuses on this approach.

2- Traffic Flow Optimization using DL algorithms

Machine learning algorithms have the ability to analyze vast amounts of data, such as historical traffic patterns, weather conditions, and events. This analysis helps to predict traffic congestion, which can be used to make real-time adjustments to traffic signals and lanes, in turn improving the flow of traffic. By adapting dynamically to changing conditions, adaptive traffic systems that use machine learning can help to reduce congestion [12].

Prediction Categories under Traffic Forecasting are [5]:

- Traffic Flow
- Travel Time
- The behavior of Vehicle & User
- Road Occupancy

Approaches to Traffic Prediction are explained in the following figure:

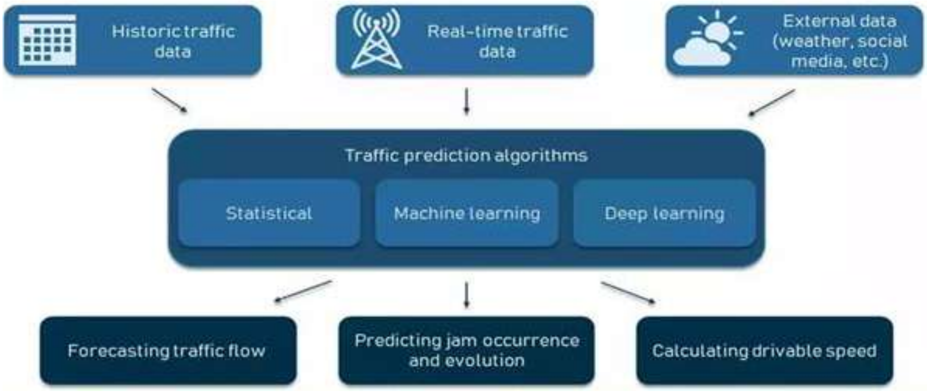

Fig 1 Approaches to Traffic Prediction [13]

3- Long Short-Term Memory (LSTM)

LSTM is a type of recurrent neural networks that uses memory cells to deal with the vanishing gradients problem. Each LSTM cell consists of four parts: three gates (input, forget, and output) and a memory cell state. The memory state is forgotten and updated by the forget and input gates, while the output gate decides which part of the memory state will be used as output. LSTM neural networks are good at handling time series data like the one we are working with in this paper [14].

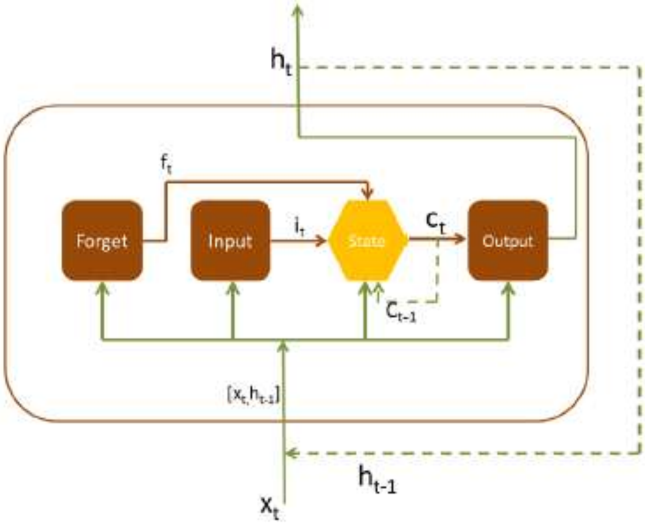

Fig 2 The architecture of LSTM [14]

2- DATASET

The dataset used in this research is DATEX II traffic data [15]. DATEX II is a set of open data provided by The Luxembourg administration of Ponts et Chaussées via the Luxembourg data platform. The data was captured by 186 cameras distributed as shown if fig 3, in the period between 19/11/2019 and 26/12/2019 on the Luxembourg motorways. The data for each camera is updated every 5 minutes, and offers the following measurements:

- Traffic Direction (from town, to town)
- Latitude and longitude of the camera
- Distance from the camera to the start of the motorway (camera at km x)
- Average speed (Km/h)
- Traffic concentration (Percentage)
- Traffic flow (Number of cars per hour)

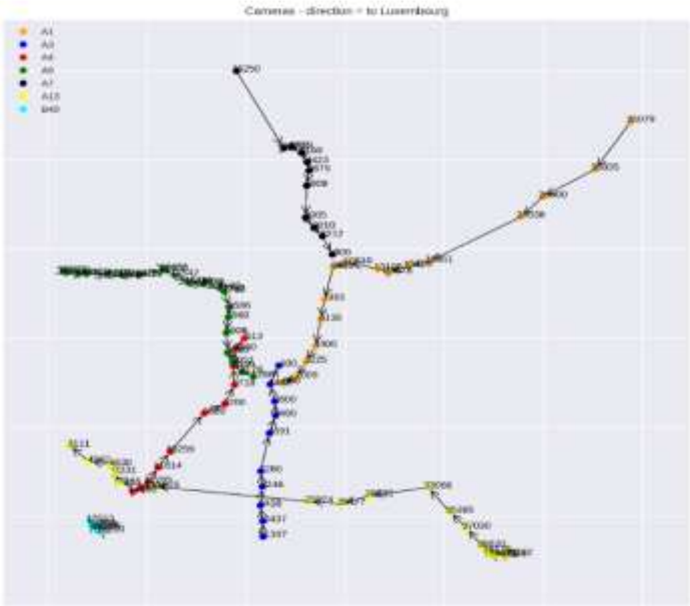

Fig 3 Cameras distribution in Luxembourg motorways.

3- Data Pre-processing

The data was divided into time series samples. Each sample consists of 4 features, each feature is 10-time steps window. The features are:

- The average speed at the studied camera 'A3.VM.7280'.
- The traffic flow rate at the studied camera 'A3.VM.7280'.
- Average speed at the previous camera 'A3.VM.8246'.
- Traffic flow rate at the previous camera 'A3.VM.8246'.
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RESULTS AND CONCLUSION:

The experiments proved that deep neural networks are the most appropriate method for traffic flow prediction. In this paper, we applied LSTM neural networks to predict traffic speed and flow rate. The suggested LSTM models consist of an Input layer followed by one LSTM layer with 128 LSTM cells, and an Output Fully Connected layer. For the optimization of this models, we use Adam optimizer with adaptive learning rates. We have trained two LSTM models: the first model predicts "Average speed" after 5, 10, or 15 minutes for one of the cameras, while the second one predicts "Traffic flow" after 5, 10, or 15 minutes for the same camera.

The required scenario was conducted on one camera, which can be generalized to any other camera out of 186 cameras distributed in the city of Luxembourg, as shown in Figure (4), with the aim of deriving the same predictions and submitting them to the decision-making support system concerned with traffic regulation in the city.

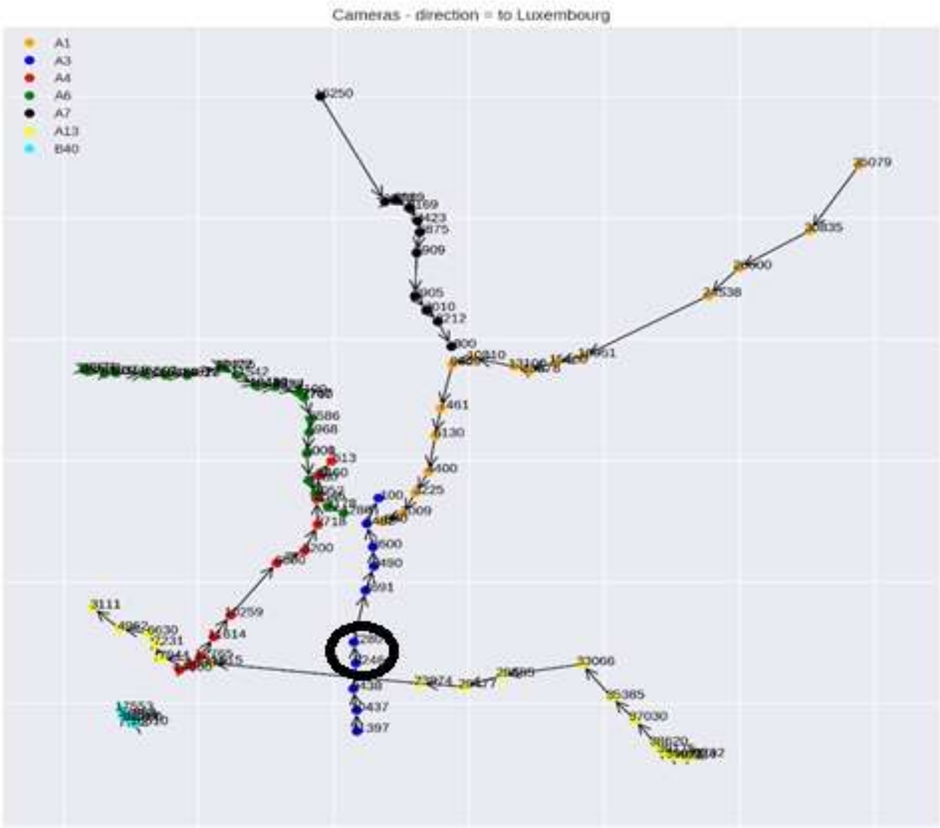

Fig 4 The position of the studied camera in Luxembourg motorways.

We have used MSE as loss function for each model. MSE is very simple and most used metric as evaluation performance metric for regression Deep Learning models.

$$MSE = \frac{1}{n} \Sigma \underbrace{\left(y - \hat{y} \right)^2}$$

The graph of MSE is differentiable, so it can be used easily as a loss function [13].
Model Evaluation is done using unseen samples from the dataset. And the evaluation metric is (RMSE):

7-1- Speed Prediction Model:

Figure (5) show training and validation loss curves for speed model:

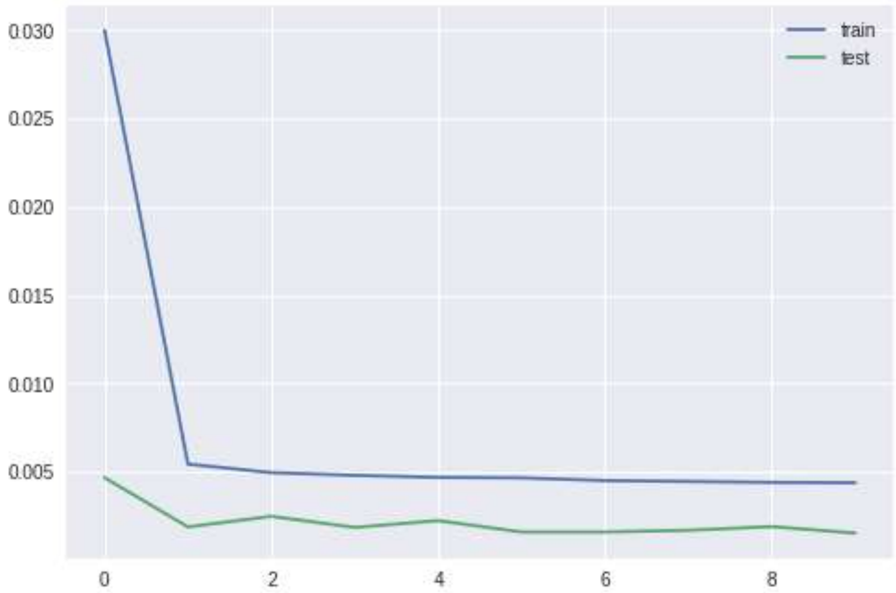

Fig 5 Speed Model loss curves

We have compared actual speed values vs predicted speed values for each period as shown in the following figures:

Fig 6 True vs Predicted Speed (5 minutes forecasting)

Fig 7 True vs Predicted Speed (10 minutes forecasting)

Fig 8 True vs Predicted Speed (15 minutes forecasting)

Table 1 Evaluation metrics for speed model

Forecasted Parameter	Period (Minutes)	RMSE
Average Speed	5	0.062
Average Speed	10	0.067
Average Speed	15	0.075

7-2- Traffic Flow Prediction Model:

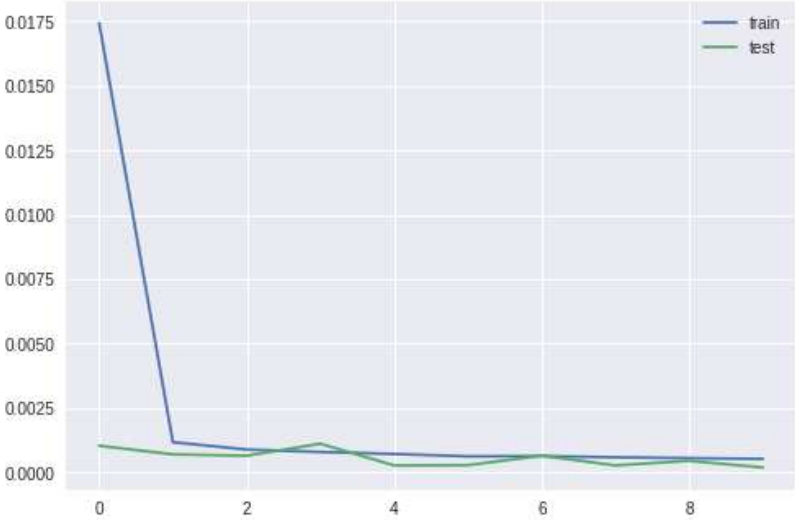

Fig 9 Traffic Flow model loss curves

We have compared actual traffic flow values vs predicted traffic flow values for each period as shown in the following figures:

Fig 10 True vs Predicted Traffic Flow (5 minutes forecasting)

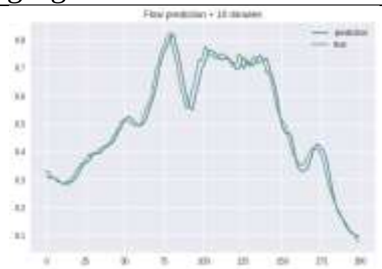

Fig 11 True vs Predicted Traffic Flow (10 minutes forecasting)

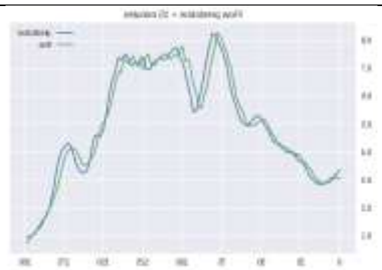

Fig 11 True vs Predicted Traffic Flow (15 minutes forecasting)

Table 2 Evaluation metrics for Traffic Flow model

Forecasted Parameter	Period (Minutes)	RMSE
Traffic Flow	5	0.017
Traffic Flow	10	0.023
Traffic Flow	15	0.029

RMSE values shown in the previous tables proves that prediction accuracy is high enough. So, the outputs of this models can be used in an assistance system to help humane operators adjust traffic signal timings and lane allocations based on the predicted traffic conditions, reducing congestion and improving flow.

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