Application Research of Big Data Technology in Intelligent Prediction of Urban Traffic Flow

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Abstract: *With the development of urbanisation and the spread of information-sensing technology, the data produced by urban traffic systems has begun to show the characteristics of big data, such as a large volume, high dimensionality, heterogeneity and strong spatiotemporal dependence. There are some good prospects and problems in the field of traffic flow prediction now. The old prediction model is no longer suitable for the current type of data and cannot handle the irregular fluctuations in space and time. The purpose of this paper is to introduce the general structure of big data technology applications in intelligent prediction of urban traffic flow. First, this paper will introduce the main characteristics of urban traffic big data and the development ideas of intelligent prediction algorithms. Next, we will present the method of multi-source data fusion processing for prediction, the structure of a spatiotemporal prediction model based on deep learning (such as graph neural networks and attention mechanisms), and a dynamic prediction integration system that supports real-time stream processing. Finally, we will introduce some application cases of the above technology in short-term high-precision prediction, simulation and deduction of congestion propagation, as well as system performance analysis and uncertainty evaluation. Big Data has been used to develop some intelligent prediction methods that can find hidden patterns in traffic conditions easily, and a good data foundation has been provided for dynamic perception and control of traffic.*

Keywords: *Traffic Flow Prediction, Big Data, Deep Learning, Graph Neural Networks, Spatiotemporal Data Mining, Uncertainty Analysis*

Introduction

The urban traffic system is a very complicated and constantly changing spatio-temporal network that affects the economy and life of the people in many ways. In order to realise the goal of intelligent management and optimisation of the traffic system, it is necessary to know how the traffic will flow. Most of the above prediction methods are either mathematical statistics or simplified physical models. The main reasons for the poor prediction accuracy and generalisation ability of modern traffic big data obtained from all kinds of sources, such as multiple sensors and mobile phone terminals, are that they have a linear or near-linear core, limited data processing capacity, and it is difficult to observe long-range spatial and temporal correlations. Research has been carried out on the application of big data technology and advanced artificial intelligence methods to automatically learn from large-scale, diverse, real-time data and accurately predict the evolutionary pattern of traffic flow; some theoretical and practical results have been achieved. The goal of this paper is to build a complete-stack technical system for intelligent traffic flow prediction based on Big Data technology, and it will cover all links in the process, from data collection and preprocessing to model construction and application analysis, explore the main techniques and use cases of this technology, and provide an organized reference for improving the accuracy, real-time capability and reliability of predictions.

1. Theoretical Basis of Big Data and Urban Traffic Flow Prediction

1.1 Analysis of Big Data Features in Urban Traffic Flow Prediction

The urban traffic system is a very complex spatio-temporal dynamic system, and the data obtained from the operation of this system are naturally in the form of big data; thus, a physical foundation for research on intelligent prediction methods has been laid. There is a large amount of data, and these have also developed in various ways, are diverse, and are changing rapidly. Fixed sensor data, such as that from inductive loops, microwave radar and video checkpoints, is very accurate but spatially discrete; GPS trajectories of floating cars and mobile signal data are continuous but have a large spatial scatter. Multimodal data from all over the place, such as social media activity, weather and special event information, can be combined to obtain a complete picture of traffic conditions.

Based on the above data, some conditions must be met for the prediction method. Due to the strong spatio-temporal correlation, the data values are not independent; rather, they are influenced by cycles, trends and other events at different times, and in space, they are constrained by the connectivity of roads and the propagation pattern of traffic waves. The data may have a low signal-to-noise ratio, and there are also problems of missing values, anomalies and asynchronicity; all of these fall under the category of problems in data preprocessing and quality improvement methods. In order to make full use of the potential value of the data in building prediction models, we need to understand and formally define the attributes mentioned above; otherwise, it will be difficult to conduct further data fusion and design a good model structure.

1.2 Exploration of Traditional Models and Their Deficiencies in Traffic Flow Prediction

Before the spread of Big Data technology, the main model system for traffic flow prediction in this area was based on classical theory and statistics. Given that the data are stationary and linear, historical averages and time-series models have been used for extrapolation; although they are computationally simple, they have strong assumptions. Macroscopic simulation models are based on the laws of traffic flow and aim to describe the collective behaviour of traffic by analogy with fluid dynamics. Microscopic simulation models are used to set up the behaviour rules of drivers, such as car following and lane changing, and then the development of traffic flow is simulated[1].

As the problems of modern city traffic have become more severe, the previous theories have shown some deficiencies. They are generally very simple abstractions of the system and therefore cannot accurately reflect the true nonlinear and stochastic nature of the system. The parameters of a model need to be changed under different circumstances, and they do not have good generalisation. More importantly, the structure of the model cannot incorporate and handle all kinds of high-dimensional, large-volume, real-time data, so this information will go unused. The first way has a small area and simple, fixed rules, so it cannot show the rich spatio-temporal correlations of a large-scale road network. They cannot learn deep, long-term spatial and temporal dependency patterns from the data automatically, and this is now the main reason why prediction accuracy has not improved.

1.3 Evolutionary Trajectory and Technical Foundation of Intelligent Prediction Algorithms

To solve the bottleneck of traditional models, the evolutionary path of prediction algorithms has been to move away from manual feature engineering and towards end-to-end automatic representation learning. Support Vector Machines and Gradient Boosting Trees were the first machine learning algorithms to increase the accuracy of prediction; although they are non-linear kernel methods and ensemble methods, their performance was still limited by the quality of feature engineering. With the development of deep learning, intelligent prediction has reached a new stage, and at the foundation of this is the automatic extraction of hierarchical feature representations from raw data by means of multi-layer neural networks.

Convolutional Neural Networks can be employed to extract local features and share weights in order to map the topology of a road network into a grid, obtain local spatial patterns and translation-invariant features efficiently, etc. Recurrent neural networks and other kinds of recurrent neural networks have been developed to process sequences of data, and they can remember information from the distant past in their internal states. In recent years, some progress has been made in this area with Graph Neural Networks. They directly model the traffic network as a graph, and the nodes are roads or areas, and the edges are the connections between them. Message passing can be used to explicitly introduce the spatial dependence of a node, and thus the basic characteristics of spatial propagation in traffic flow can be shown more naturally and accurately. The main reason for this progress is that the representational power of prediction models has been continuously enhanced; thus, they can be directly trained on big data and simulate the inherent complexity of urban traffic.

2. Construction of Big Data Technology Methods for Intelligent Traffic Flow Prediction

2.1 Collection and Fusion Processing of Multi-Source Heterogeneous Traffic Data

The first step in building a good prediction model is to organise and integrate the raw data properly. At the time of data collection, all kinds of data are obtained from physical sensors, mobile phones, the World Wide Web, etc. Organised data refers to organised data; it is exampleled by the frequency data of inductive loops and spatiotemporal trajectory coordinates of floating cars, whereas unstructured data is such as video streams from traffic cameras and text-based event reports. Generally speaking, the raw data have problems such as different spatio-temporal scales, irregular sampling frequencies, various formats and uneven quality; they are very noisy if used directly. Therefore, we will construct a single Data Cleaning and Augmentation Pipeline. The first is to identify and correct outliers, then to fill in the missing data, and finally to resample the data and align the different time scales.

First of all, the aim of data fusion is to obtain all the spatial-temporal information. Generally speaking, there are many levels of fusion: At the data level, observations from all sources are mapped to a single road network partition and timestamp by means of spatio-temporal matching and coordinate transformation; at the feature level, embedding methods in deep learning are employed to convert categorical data, spatial coordinates and temporal information into dense numerical vectors, and then these are combined with continuous sensor data; at the decision level, some network designs have special fusion modules that adjust the weight given to different data sources according to the current spatio-temporal conditions. A good fusion process can increase both the signal-to-noise ratio and the dimension uniformity of the input data, and at the same time, complex correlations among traffic conditions that cannot be obtained from any single source can be discovered; thus, a high-quality data foundation will be provided for the construction of the model[2].

2.2 Deep Learning-Based Traffic Flow Prediction Model Architecture

Based on all kinds of spatio-temporal correlations in the development of traffic flow at present, a deep learning-based prediction model will be employed to offer all-weather prediction services. The main direction of development for architecture now is to better model spatio-temporal graph data together. It is generally a Spatio-temporal Convolutional Network; a Graph Convolutional Network is used to obtain the spatial features first, and then one-dimensional convolutions or gated recurrent units are employed to model the temporal changes. Graph Convolutional Networks can be used to introduce convolutional operations in either the spectral or spatial domain to learn the spatial relationships among nodes directly for the topology of a traffic network, and thus overcome the limitations of traditional convolutional neural networks that are based on Euclidean grid data.

To solve the problems of long-term dependency and variation in space and time for traffic forecasting, many new models have introduced attention mechanisms and adaptive graph learning. A Spatiotemporal Attention Mechanism can be used to focus on the relevant time step and the highly influential spatial node in the road network at that time, and give less weight to all other spatiotemporal information. There are other reasons as well, such as traffic jams in the morning and rush hour. The adaptive graph learning module will not use the fixed graph structure obtained in the previous step of road network topology, but will learn a new one independently to find potentially different correlation strengths among nodes in the data. Thus, one can obtain some implicit spatial information about traffic from the flow of traffic. According to the modules in the architecture above, a good nonlinear mapping function can be constructed to extract good spatio-temporal features from a large amount of historical data.

2.3 Integration of Real-Time Data Stream Processing and Dynamic Prediction Algorithms

Finally, the aim of the intelligent prediction system is to handle the flow of real-time data and make dynamic online predictions. Therefore, the trained prediction model should be put in a stream processing framework to build a low-latency and high-throughput online service pipeline. A Distributed Stream Processing Engine is generally used in the Data Stream Processing Layer. Continuously collect the raw data from all the sensors, and at the same time parse, filter, clean, calculate the preliminary window aggregation results for this data, and finally provide this processed structured stream to the prediction model with very low latency.

The basis of dynamic prediction algorithms is to obtain new values for the model parameters and then perform prediction inference in real time. With the change in the situation of traffic over time, the accuracy of a fixed model will decline. Therefore, one should design an online learning method or a periodic incremental learning method that can adjust the model's parameters according to the new data and continue to obtain good prediction results. At inference time, the model needs to have a response speed of a few milliseconds, so pruning and quantization of the model, as well as special hardware acceleration, should be employed. The whole integrated system needs to be organised reasonably in terms of resources and handle faults; it should guarantee the stability and reliability of the prediction service under a large number of simultaneous data inputs, build a closed-loop intelligent decision-support capability based on the flow of real-time data and the output of prediction results[3], etc.

3. Analysis of Intelligent Traffic Flow Prediction Applications Based on Big Data

3.1 High-Precision Short-Term Traffic Flow Prediction and Spatiotemporal Pattern Mining

The first use of intelligent prediction models based on big data technology is to forecast traffic flow at a certain time in the near future. The above models can forecast traffic changes in various places and at different times for the next 5 minutes to an hour. The output is not a single number but an interval prediction or a probability distribution of the corresponding indices, such as traffic volume, speed and occupancy rate. The first direct purpose of this high-precision prediction is to give people advance notice of changes in traffic conditions so that they know whether there will be a reduction in speed or traffic congestion at a certain time. The increase in the accuracy of the prediction is due to a better representation of the nonlinear characteristics of microscopic traffic flow by the model; for instance, all kinds of fluctuations caused by changes in signal phases and temporary traffic jams can be modelled more realistically, as well as the platooning and dispersion of vehicle convoys.

More importantly, good prediction results can also be used to find the internal spatial and temporal patterns of the traffic system. Based on many comparisons of historical prediction sequences with the actual data, and by observing the internal representations learned by the model, one can infer the pattern of spatiotemporal evolution in traffic flow indirectly. Determine the main origins and spread paths of traffic jams in the road network, quantify the statistical regularity of traffic conditions at different times and in bad weather, and uncover hidden correlations among all parts of traffic. These are not the traditional empirical knowledge; rather, they are data-driven pieces of information on the connection between the large-scale behaviour and the small-scale structure of urban traffic systems. Therefore, prediction is no longer only about 'forecasting'; it has also become a way to 'understand' the problems in a system.

3.2 Simulation and Deduction of Traffic Flow Propagation in Complex Road Network Environments

Since it is very accurate at short-term forecasting, the new function of extending the intelligent prediction model will be to simulate and infer the spread of traffic flow in a complex road network. It is not a typical micro-simulation, but rather a trained deep learning model will be used as a shortcut 'digital twin' kernel. Based on the initial road network and boundary conditions, a few forward iterations will be carried out to find out how traffic congestion and other unforeseen events change over time and in space. Deduction can be used to consider the effect of all areas in light of some changes; for example, one can predict how traffic jams will occur and spread in the surrounding places after a main road is closed[4].

The main reason for this is that the model has a spatiotemporal dependence model. With learning, the improved Graph Neural Network model has acquired all sorts of influence weights for the nodes in the road network. Deduction is used to determine how much each section of the road will be affected by the upstream, downstream and even more distant parts of the network based on the current condition of the whole network, and thus achieve a realistic simulation of traffic wave propagation. Based on the above analysis, we do not need to set all the small-scale behaviour parameters in the traditional simulation model. Induction can be used to find the general distribution pattern of historical observation data, and it can also be employed as a good computational-experimental platform to assess the resilience of road networks, analyze the reasons for bottlenecks, and forecast the possible impact of management measures.

3.3 Performance Evaluation and Uncertainty Analysis of Prediction Systems

The operation of the deployed and used intelligent prediction system should be regularly observed, and any uncertainty in the results needs to be resolved. Many different indicators under different circumstances need to be used in the evaluation of performance, not just the mean absolute error and root mean square error. Investigate how stable the model's predictions are at different levels of temporal granularity and under various traffic conditions by analysing the distribution of errors in off-peak and peak hours and in free-flow and congested traffic, etc. Evaluation in the spatial dimension is also necessary; one should examine the prediction results of the model for roads of different categories and nodes at various locations in the topology to find any shortcomings in the model. Given the computational efficiency and resource requirements of the model in the evaluation stage, it should be confirmed that it can meet the real-time demands of online applications[5].

Uncertainty analysis of the prediction results should be carried out to make the next scientific decision based on the model. Traffic systems are inherently random, so there will be some noise in the data collection process and simplifications in the model; thus, any prediction will have a certain degree of uncertainty. The upper bound of the error for the intelligent prediction model should be known. Quantile regression can be employed to obtain prediction intervals at different levels of confidence, and a Bayesian deep learning framework can be used to find the posterior probability distribution of the predicted values. The first is to list all the main reasons for uncertainty. Generally speaking, the reasons for the above are that there is noise and missing data at the level of data quality, approximation errors between the model structure and complex real-world relationships, and unforeseen external events in the traffic system that are difficult to predict or model. To improve the reliability and generalisation of the prediction results, one can systematically quantify, attribute and visualise uncertainty. It will set an upper bound for the risk of the following decisions based on predictions, such as route guidance, signal control and demand management; thus, the general reliability and scientific nature of intelligent transportation system applications will be improved[6].

Conclusion

Organize the application framework of big data technology for intelligent urban traffic flow prediction systematically in this paper and cover all links in the chain, from the analysis of data characteristics and intelligent algorithm principles to the construction of specific technical methods and application analysis. Based on the above research, given that traffic big data has many kinds of heterogeneity and strong spatiotemporal correlation, new predictive methods are needed. Graph neural networks, spatio-temporal attention mechanisms and other kinds of deep learning model structures can be employed to gather information from all places and automatically learn complex nonlinear spatiotemporal correlations in road networks. Therefore, we can know the traffic conditions in the near future and how they will change. In actual operation, the results obtained after applying the intelligent prediction system should have a good data fusion processing workflow, efficient real-time computational integration, and an organised way to evaluate the performance and uncertainty of the prediction results. In the future, more research will be carried out to develop more interpretable prediction models, explore adaptive prediction in few-shot and zero-shot situations, further study the combination of prediction uncertainty and dynamic decision-making, and build efficient and scalable real-time prediction systems for large-scale urban road networks. With the continuous development of technology and innovation, big data intelligent prediction will be used to analyse and address the problems of large-scale urban traffic.

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