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Short-term forecasting of passenger demand under on-demand ride services: A spatio-temporal deep learning approach

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ABSTRACT

Short-term passenger demand forecasting is of great importance to the on-demand ride service platform, which can incentivize vacant cars moving from over-supply regions to over-demand regions. The spatial dependencies, temporal dependencies, and exogenous dependencies need to be considered simultaneously, however, which makes short-term passenger demand forecasting challenging. We propose a novel deep learning (DL) approach, named the fusion convolutional long short-term memory network (FCL-Net), to address these three dependencies within one end-to-end learning architecture. The model is stacked and fused by multiple convolutional long short-term memory (LSTM) layers, standard LSTM layers, and convolutional layers. The fusion of convolutional techniques and the LSTM network enables the proposed DL approach to better capture the spatio-temporal characteristics and correlations of explanatory variables. A tailored spatially aggregated random forest is employed to rank the importance of the explanatory variables. The ranking is then used for feature selection. The proposed DL approach is applied to the short-term forecasting of passenger demand under an on-demand ride service platform in Hangzhou, China. The experimental results, validated on the real-world data provided by DiDi Chuxing, show that the FCL-Net achieves the better predictive performance than traditional approaches including both classical time-series prediction models and state-of-art machine learning algorithms (e.g., artificial neural network, XGBoost, LSTM and CNN). Furthermore, the consideration of exogenous variables in addition to the passenger demand itself, such as the travel time rate, time-of-day, day-of-week, and weather conditions, is proven to be promising, since they reduce the root mean squared error (RMSE) by 48.3%. It is also interesting to find that the feature selection reduces 24.4% in the training time and leads to only the 1.8% loss in the forecasting accuracy measured by RMSE in the proposed model. This paper is one of the first DL studies to forecast the short-term passenger demand of an on-demand ride service platform by examining the spatio-temporal correlations.

1. Introduction

The on-demand ride service platform, e.g., Urber, Lyft, DiDi Chuxing, is an emerging technology with the boom of the mobile internet. Ride-sourcing or transportation network companies (TNCs) refer to an emerging urban mobility service mode that private car owners drive their own vehicles to provide for-hire rides (Chen et al., 2017). On-demand ride-sourcing services can be completed via smart phone applications. The platform serves as a coordinator who matches requesting orders from passengers (demand) and

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vacant registered cars (supply). There exists an abundance of leverages to influence drivers' and passengers' preference and behavior, and thus affect both the demand and supply, to maximize profits of the platform or achieve the maximum social welfare. Having a better understanding of the short-term passenger demand over different spatial zones is of great importance to the platform or the operator, who can incentivize drivers to the zones with more potential passenger demands, and improve the utilization rate of the registered cars.

Although limited research efforts have been implemented on forecasting short-term passenger demand under the emerging on-demand ride service platform in most recent years mainly due to the real-world data unavailability, the fruitful studies on the taxi market can provide valuable insights since there exist strong similarities between the taxi market and the on-demand ride service market. A series of mathematical models were developed to spell out endogenous relationships among variables in the taxi market (; Yang et al., 2002, 2005, 2010b; Yang and Yang, 2011) under the two-sided market equilibrium. On the demand side, the accurate passenger demand was affected by passengers' waiting time and taxi fare; while on the supply side, drivers' behavior, i.e., how to find a passenger, was mainly affected by the expected searching time and taxi fare. The passenger demand was endogenously determined when the taxi operator decided the taxi fare structure and the number of released licenses of taxis (entry limitation).

In theory, the equilibrium between the demand and supply will eventually be reached when the arrival rate of passengers equals to the arrival rate of vacant taxis and equals to the meeting rate. However, heterogeneous and exogenous factors in reality, e.g., the asymmetric information, and short-term fluctuations, may make it difficult to guarantee the spatial distribution of taxis matching the passenger demand all the time (Moreira-Matias et al., 2013). Hence, disequilibrium states can result from the following two scenarios: oversupply (an excess in the number of vacant taxis may decrease the taxi utilization) and overfull demand (excessively waiting passengers may lower the degree of satisfaction). Both scenarios are harmful to the taxi operator as well as the on-demand ride service platform, raising a strong need for a precise forecasting of short-term passenger demand. It helps the operator/platform implement proactive incentive mechanism, such as surge pricing and cash/point awards, to attract drivers from regions of oversupply to regions with overfull demand. These strategies not only shorten the process of reaching equilibrium under a dynamic environment but also help improve the taxi/car utilization rate and reduce passengers' waiting time.

However, short-term forecasting of passenger demand or on-demand ride services in each region is of great challenge mainly due to the three kinds of dependencies (Zhang et al., 2017b):

(1) Time dependencies: the passenger demand has a strong periodicity (for example, the passenger demand is expected to be high during morning and evening peaks and to be low during sleeping hours); furthermore, the short-term passenger demand is dependent on the trend of the nearest historical passenger demand.
(2) Spatial dependencies: Yang et al. (2010b) revealed that the passenger demand in one specific zone was not merely determined by the variables of this zone, but endogenously dependent on all the zonal variables in the whole network. Generally, the variables of the nearby zones have stronger influences than distant zones, which inspires the need for an advanced model that can capture local spatial dependencies.
(3) Exogenous dependencies: some exogenous variables, such as the travel time rate and weather conditions, may have strong influences on the short-term passenger demand. The exogenous variables also demonstrate time dependencies and spatial dependencies.

Although little direct experience suggests solutions to these three dependencies in short-term passenger demand forecasting, studies on traffic speed/volume prediction and rainfall nowcasting provide valuable insights (Ghosh et al., 2009; Huang and Sadek, 2009; Guo et al., 2014; Wang et al., 2014). Recently, deep learning (DL) approaches have been successfully used for traffic flow prediction. For example, Ma et al. (2015a) employed the long short-term memory (LSTM) neural network to capture the long-term dependencies and nonlinear traffic dynamics for short-term traffic speed prediction. Zhang et al. (2017b) presented a deep spatio-temporal residual network to predict the inflow and outflow in each region of a city simultaneously. Shi et al. (2015) innovatively integrated CNN and LSTM in one end-to-end DL structure, named the convolutional LSTM (conv-LSTM), which provided a brand-new idea for solving spatio-temporal sequence forecasting problems. In that research, the numerical experiments showed that the conv-LSTM outperformed fully connected LSTM in two datasets.

In this paper, we propose a novel DL structure, named the fusion convolutional LSTM network (FCL-Net), to consider the three dependencies simultaneously in the short-term passenger demand forecasting for the on-demand ride service platform. Different from the aforementioned studies, this structure coordinates the spatio-temporal variables and non-spatial time-series variables in one end-to-end trainable model. Before feeding these explanatory variables into the DL structure, a tailored spatial aggregated random forest is designed to evaluate the feature importance with different categories, look-back time intervals, and spatial locations.

To the best knowledge of the authors, this paper is one of the first attempts to employ spatio-temporal DL approaches in short-term passenger demand forecasting under the on-demand ride service platform. The main contributions of this paper are within three folds:

(1) The novel FCL-Net approach characterizes the spatio-temporal properties of the spatio-temporal predictors, captures the temporal features of non-spatial time-series variables simultaneously, and coordinates them in one end-to-end learning structure for the short-term passenger demand forecasting.
(2) We propose a spatial aggregated random forest to extract the potential predictors affecting short-term passenger demand and assess the feature importance of them.
(3) Validated by the real-world on-demand ride services data provided by DiDi Chuxing in a large-scale urban network, the proposed