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Short-term freeway traffic parameter prediction: Application of grey system theory models

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ABSTRACT

Intelligent transportation systems applications require accurate and robust prediction of traffic parameters such as speed, travel time, and flow. However, traffic exhibits sudden shifts due to various factors such as weather, accidents, driving characteristics, and demand surges, which adversely affect the performance of the prediction models. This paper studies possible applications and accuracy levels of three Grey System theory models for short-term traffic speed and travel time predictions: first order single variable Grey model (GM(1,1)), GM(1,1) with Fourier error corrections (EFGM), and the Grey Verhulst model with Fourier error corrections (EFGVM). Grey models are tested on datasets from California and Virginia. They are compared to nonlinear time series models. Grey models are found to be simple, adaptive, able to deal better with abrupt parameter changes, and not requiring many data points for prediction updates. Based on the sample data used, Grey models consistently demonstrate lower prediction errors over all the time series improving the accuracy on average about 50% in Root Mean Squared Errors and Mean Absolute Percent Errors.

1. Introduction

Intelligent transportation systems such as advanced traveler information systems, real-time route guidance, and emergency response systems employ real-time traffic parameters. Accurate and robust prediction of these parameters (i.e., speed, travel time (TT), flow, occupancy) is a critical problem so that any improvement would yield more efficient transportation management and control strategies. For instance, better real-time dynamic routing can result in avoiding congestion or finding the fastest way to a destination for transporting people and goods (Cheng, Gau, Huang, & Hwang, 2012). On the contrary, traffic often exhibits unexpected or expected changes due to various external factors such as incidents, inclement weather, special events, and driver behaviors that adversely affect the performance and accuracy of prediction models. This paper presents online adaptive methods based on the Grey System theory for reliable and robust short-term traffic predictions on freeways. The focus traffic parameters are average speed and travel time since (1) they are key parameters highly impacted by the aforementioned external factors as well as covariates such as weather, demand surges, driver characteristics, road work, and roadway geometry information that are not necessarily stamped together with observed data and (2) they are critical parameters used in wide range of traffic management and control, level of service analysis, planning, and safety applications in transportation field. This prediction problem closely fits to the philosophy of Grey System Theory as parameters are induced by covariates that can be left out from the observed data causing an incomplete (Grey) system (Liu, Lin, & Forrest, 2010) which actually has been utilized by many researchers for time series modeling. In addition, traffic data generation processes (DGPs) may not be necessarily independent and identically distributed (i.i.d), due to different locations or sudden shifts that lead to non-stationarity and nonlinearity. Hence, prediction models need to incorporate possible changed dynamics via updating model parameters (i.e., retraining) ideally inherently with low amount of data and computational complexity.

Past applications of Grey System theory include but not limited to short-term forecasts of stock market, foreign exchange rates, and customer demand (Kayacan, Ulutas, & Kaynak, 2010). Specifically in transportation, the applications of the theory mainly have been on volume, traffic accident, and pavement design. Among them, GM(1,1) is combined with a Markov transition matrix by Zhang (2010) to forecast annual average daily traffic data. A comparison study by An, Cui, and Zhao (2012) presents performance of GM(1,1) against back propagation neural network (NN) and radial basis function NN. The study predicts monthly average daily traffic

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volume and reports that GM(1,1) provides highest accuracy. In order to address seasonality, revised GM(1,1) models with periodic trigonometric terms are derived and applied for hourly volume forecasting (Man, Chen, & Xiao, 2012; Shuhua & Xinping, 2010). Similarly in Gao, Zhang, and Cao (2010), GM(1,1) is compared with support vector machine (SVM) and artificial NN models for predicting average hourly volumes. Some researchers used Grey models in hybrid scheme to enhance forecasting capabilities. Cubic exponential smoothing and GM(1,1) models are combined in Liu, Qin, Dong, Yang, and Tian (2014). According to the study when combined, resulting weighted model provided lower errors on monthly volume data. In a more detailed study, GM(1,1) with Autoregressive Integrated Moving Average (ARIMA) and generalized regression NN models are compared by Yu, Sun, Sun, and Yang (2015). The paper also tests possible combinations of models with fixed and Elman NN-based weights a framework similar to forecast encompassing. The study uses monthly volume data and reports highest accuracy with Elman NN-based weighted forecasts while individually GM(1,1) provides the lowest errors. Although it fits to low data demand characteristic of GM, testing datasets in these studies range from 8 to 54 samples which may be very low for a fair comparison considering NN and ARIMA model training. In other traffic applications, accident forecasting problem is discussed in Na, Shuangwei, Jianfeng, Chaoyang, and Xiaoyan (2010). Likewise, a version of Grey Verhulst model is applied to forecast annual high speed road accident in Jie et al. (2015). From highway engineering, GM(1,1) is also applied for pavement roughness index and permanent deformation estimations (Du & Shen, 2005; Jiang & Li, 2005). Certainly, prediction performance of Grey System models on speed or travel times is missing in the literature. In fact, Van Hinsbergen, Van Lint, and Sanders (2007) in taxonomy of different short-term prediction models list a clear need of reporting performance of GMs. Moreover, in the review article specifically on artificial intelligence, Van Lint and Van Hinsbergen (2012) do not list yet any GM applications. Thus, the theory and the corresponding Grey models represent an interesting tool that yet to be investigated in detail for traffic systems and compared with existing competing models.

Short-term traffic prediction is one of the well-developed areas in transportation. In a broad sense, researchers have investigated a number of parametric and nonparametric methods for traffic flow, speed, travel time, and occupancy. Between these two main categories, boundaries can be flexible. If definitions from Van Hinsbergen et al. (2007) are adopted, a model can be thought parametric when structure is fixed and parameters learned from data. From this perspective, Grey system models can be listed within parametric models. Other models in this set commonly include macroscopic and microscopic simulations, regression, time series, Kalman Filters (KF), and their variations. Likewise, with both parameters and model structure are determined from data through training, nonparametric methods consist of non-parametric regression, fuzzy logic, k-Nearest Neighbor (k-NN), regression trees, Bayesian Networks (BN), support vector machines (SVM), neural networks (NN), and variations of these methods. For detailed reviews, the state-of-the-art on short-term forecasting models, and their critical aspects, the reader is referred to works by Smith and Demetsky (1997), Smith, Williams, and Oswald (2002), Vlahogianni, Golias, and Karlaftis (2004), Vlahogianni and Karlaftis (2011), Van Lint and Van Hinsbergen (2012), Vlahogianni, Karlaftis, and Golias (2014). In the most recent review, Vlahogianni et al. (2014) count current challenges as combination of existing models, longer prediction horizons with the help of large historical datasets, impact of spatial correlations and transferability, simplicity, adaptability to different data types, handling data with missing, continuous or discrete, different noise and aggregation levels. Consistent with these points, freeway speed and travel time predictions have been indeed switching towards addressing such issues. Among these research, a hybrid support vector based Chaos theory and wavelet analysis method is proposed that enhances accuracy of classical SVMs by appropriate wavelet kernel choice for non-stationary DGP and efficient model structure parameter optimization (Wang & Shi, 2013). Accuracy of the presented method is compared against classical SVM. As a variation of NN, long short-term memory NN is adopted by Ma, Tao, Wang, Yu, and Wang (2015) to improve adaptability of NNs in case of change points in long-term predictions. The method optimizes time lags to train temporal sequence processing and reports better accuracy over SVM, KF, and other NN models. Generally, NNs are trained on larger datasets, and so considerable deviations from learned patterns may yield poor predictions. A space-time delay neural network model is developed by Wang, Tsapakis, and Zhong (2016) to address spatial and temporal autocorrelation on roadway network. The proposed method performs better prediction results over naive, simple ARIMA, and space-time ARIMA models from 5 to 30-minutes horizons. The method acknowledged to be missing online training mechanism and the computational time can be a concern for real-time implementations on simple device applications. Although NN-based models can report better accuracies, interpretation of results are rather difficult and the models need retraining in case of a locational transfer. A regression tree model with gradient boosting is developed by Zhang and Haghani (2015) where ensemble of regression models are fitted to produce forecasts under varying conditions. The method considers only temporal correlations and requires retraining in terms of transferability, and demands relatively higher computational power. However, it is designed to handle data from different sources or collection technologies. Better results are obtained compared to basic ARIMA models up to 6-step predictions and improved accuracy is reported over random forest method until 3-step predictions. A classical machine learning technique, hidden Markov model (HMM), is tested up to 5-min traffic condition prediction on freeways using speed data (Qi & Ishak, 2014). The study compares results with naive models and reports improvements. HMMs are able to produce conditional state probabilities given previous observations. Main drawback can be assumption of an underlying DGP distribution, higher computational time in case of high dimensional state transition, and need of retraining to update estimated state distributions. Location depended k-NN method is presented by Cai et al. (2016) in an attempt to address similarity in historical data and spatial correlations. The method uses large datasets for up to an hour-step speed predictions. Results are better in single-step, however, comparable especially at 1-h. A particle filter with non-explicit state transition models is developed by Chen and Rakha (2014) for travel time prediction. The method is based on identification of similar behaviors in historical data and compared to KF and k-NN models. It reports better accuracy especially after 1-step predictions up to 1-h horizon. Similar to NNs, any pattern not fed to this method such as a different change would be interesting to test. Thus, historical pattern learning might also need to be repeated for a different location. In another study involving large historical datasets, a Monte Carlo simulation-based traffic speed forecasting is presented for an entire city (Jeon & Hong, 2015). Only computational architecture and implementation using R-project are provided.

In sum, prediction models in traffic as well as other fields are switching towards data intensive artificial intelligence models or expert systems. However, concerns with these approaches are black box framework, training difficulties, sensitivity analysis, and quick, stochastic and uncontrollable convergence (e.g., metaheuristics) (van Zuylen, 2012). Based on this, Grey System theory models for traffic parameter prediction can be good candidates with simple interpretable structure, less data demanding, adaptive, and transferable for network applications. Based on these motivations, this study applies GMs to short-term average traffic