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Wavelet-Bayesian Hierarchical Stochastic Model for Short-Term Traffic Flow at Non-critical Junctions

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Introduction:

The major existing Urban Traffic Control Systems (UTCS) (like, SCATS and SCOOTS) collect traffic condition related data for real-time monitoring and operational purposes. In an Intelligent Transportation Systems (ITS) equipped transport network one of the important uses of traffic data collection is continuous forecasting of traffic conditions in near (short-term) future based on the current traffic conditions.

The existing short-term traffic forecasting algorithms require large datasets from historical observations and are heavily dependent on data from recent past, available through continuous monitoring of traffic conditions. However, due to financial and operational constraints, generally the continuous collection of traffic condition related data is limited to the critical junctions in an urban signalized transport network. These junctions are 'critical' in the sense that the signal control plans under any existing UTCS (for example SCATS in Dublin) are decided based on the real time traffic condition information from the junctions. All other junctions within the signalized network other than the critical junctions can be considered 'non-critical'. Hence, for non-critical urban signalized junctions where data related to traffic conditions (e.g. volume, speed or density) are not collected regularly or for junctions where the data collection system (inductive loop-detector or video imaging system) is out of service for a considerable period of time, the existing short-term traffic forecasting algorithms cannot be applied due to unavailability of data on real time traffic conditions.

This paper develops a random process model to simulate short-term traffic flow time-series datasets that can be used in such situations. The proposed model is formulated based on a combination of discrete wavelet transform (DWT) and Bayesian hierarchical methodology (BHM).

Research Design:

TREND+BHM (TBHM) MODEL

A novel formulation of a hybrid model (TBHM) using a combination of the DWT technique and the BH model to simulate daily short-term traffic flow time-series dataset at urban signalized intersections has been proposed. The proposed TBHM model consists of two parts,

1. Non-functional Trend Model
2. Bayesian Hierarchical Residual Model

NON-FUNCTIONAL TREND MODEL

The 'trend' of a time-series data can loosely be defined as the 'long-term' change of the mean level of the data. In the daily trend model of the traffic flow observations from an urban signalized intersection, the word 'long-term' indicates stability over time on a daily basis.

In this study, DWT associated with the basis Daubechies' 4 (db4) is used to decompose the signal (time-series traffic flow observations) into different time-scales. Initially, the original signal is decomposed into approximation coefficients c_1 (low frequency/fluctuations or variability) and detail coefficients d_1 (high frequency/fluctuations or variability). The approximation coefficients c_1 (relative low frequency components) are again decomposed to approximation coefficients c_2 and detail coefficients d_2 at the next level. This procedure is repeated for further decompositions. The aim of repeating the decomposition procedure is to find an optimum approximation level for extracting the trend in the data. At optimum approximation level the reconstructed approximation coefficients, A_m (m is the optimum approximation level), become the optimal smoothed estimate of the traffic flow dataset which can truly represent the traffic flow pattern on an average day.

BAYESIAN HIERARCHICAL RESIDUAL MODEL

The residuals are obtained by subtracting the 'regular trend over an average day' from the original traffic volume observations. The modeling of the residuals helps to establish a tight simulation interval over the 'trend'.

The BH model is a parametric statistical model with a tree-like structure based on the dependencies of the variables. The parameters of the model at each stage are represented by other parametric statistical models at the next stage.

In this study, the variance of the residuals is assumed to be dependent on time. If R is the vector of the residuals then in a normal hierarchical model,

$$\boldsymbol{R}_t \sim \mathrm{N}\left(m, \boldsymbol{\sigma}_t^2\right) \qquad t = 1, 2....T$$

where, *m* is the sample mean of the residuals and σ_t is the standard deviation of the residuals for each time instant denoted by a subscript *t*. The variance of the residual dataset changes with the time of the day. To model this time-varying variance, the following parametric distribution is proposed.

$$\boldsymbol{\sigma} \sim \mathrm{LN}\left(\log(\boldsymbol{y}), \tau^2\right)$$

For the Bayesian inference of the unknown parameters, the posterior density of the normal hierarchical model is

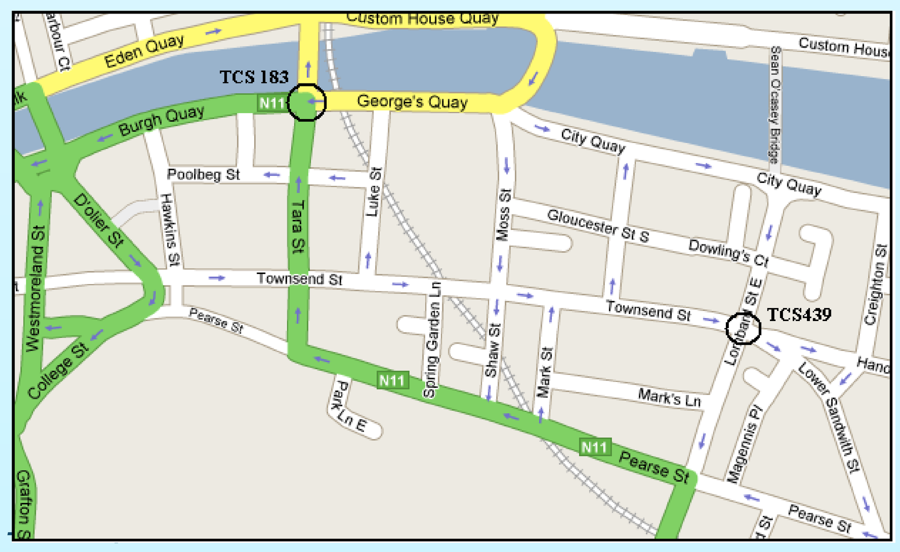
$$p\left(\xi \middle| \boldsymbol{R}, \boldsymbol{t}\right) = p(\tau) L\left(\boldsymbol{\sigma} \middle| \boldsymbol{R}, \boldsymbol{t}\right) L\left(\tau \middle| \boldsymbol{\sigma}, \boldsymbol{t}\right)$$

By integrating out the other unknown parameters except for the one whose distribution is to be estimated, the 'marginal distributions' of each of the unknown parameters can be determined. The computation of the marginal distributions of the unknown parameters in the above formulation involves evaluation of a complex integral with problems of high dimensionality. In this paper, Markov Chain Monte Carlo (MCMC) method, a particular iterative variation of the Monte Carlo simulation techniques, is used to simulate the marginal probability distributions of the unknown parameters.

The effectiveness and the accuracy of the model have been compared with a conventional short-term traffic flow forecasting time-series model based on Holt-Winters Exponential Smoothing (HWES) technique. Both the models are applied at two signalized intersections at the city-center of Dublin and their performances have been discussed.

ILLUSTRATIVE EXAMPLES

As illustrative examples, univariate short-term traffic volume data are simulated and predicted for two representative junctions (TCS 183 and TCS 439) at the city-centre of Dublin on 12th and 13th July 2005 using the proposed TBHM model and the conventional HWES model respectively.



Figure

The univariate traffic flow time-series observations, used for modeling, are obtained from the inductive loop-detectors embedded in the streets of the junctions TCS 183 (critical junction) and TCS 439 (non-critical junction) as a part of the UTCS data collection system of the city of Dublin. The data used for modeling were recorded from 15th June 2005 midnight to 13th July 2005 midnight.

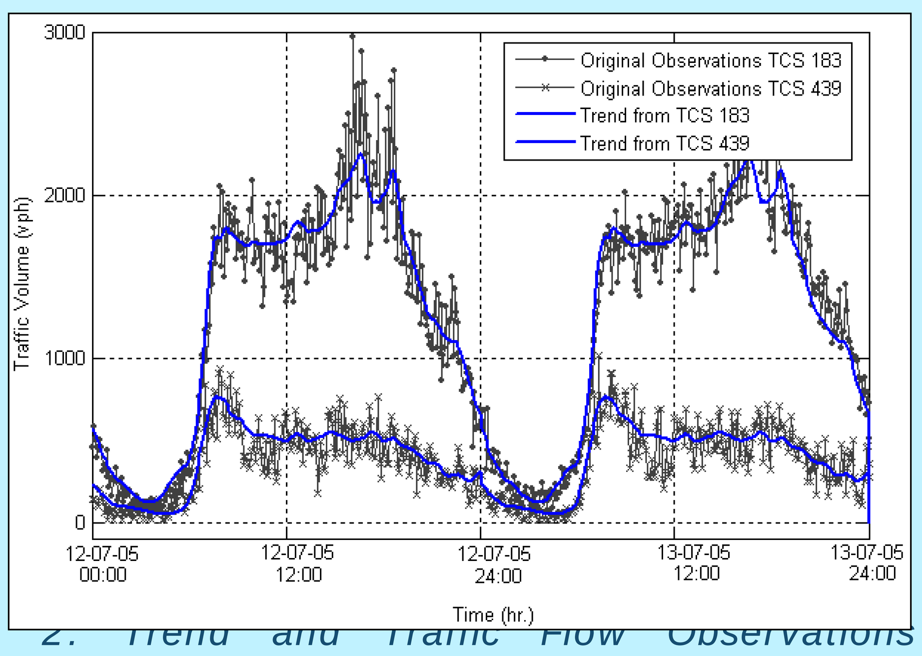


Figure 2: Trend and Traffic Flow Observations from Junctions TCS 183 and TCS 439

A 5 min. data aggregation interval is chosen for this paper. the modeling is essentially carried out on the data observed during weekdays as in case of an urban transport network, the weekend travel dynamics is inherently different from the travel dynamics in the weekdays.

The traffic flow observations over 20 days from the two chosen sites are decomposed into three levels of resolution using MRA. At each level, during decomposition the high frequency part of the data is separated from the low resolution or the low frequency part. The low frequency part at level 3 is used as a representative of the overall trend over a day in the traffic data. To model the representative trend, an average over 20 days of the reconstructed flow using level 3 approximations is considered. The selection of the average coefficients helps to reduce the effect of certain abrupt daily changes (introducing the effect of smoothing). In figure 2, the 'regular trend over an average day' is plotted over the traffic flow observations on 12th July, 2005 from junctions TCS 183 and TCS 439.

The residuals are obtained by subtracting the 'regular trend over an average day' from the original observations. The time varying variance of the residuals are simulated using BH model.

COMPARISON OF RESULTS

The results from the proposed TBHM model and the conventional HWES model are compared based on their accuracy (quantitative) and effectiveness (conforming to the nature of variation). The quantitative comparison of accuracy has been carried out by comparing the error estimates from both the models (Table 1) and the proposed TBHM model has been proved to be superior to the HWES model.

	Mean of Observations (12-07-05) (vph)	Mean of Observations (13-07-05) (vph)	MAPE from TBHM Model (12-07-05)	MAPE from TBHM Model (13-07-05)	MAPE from HWES Model (12-07-05)	MAPE from HWES Model (13-07-05)
TCS 183	1300.83	1253.9	19.99%	12.83%	21.75%	23.07%
TCS 439	374.7	362.8	27.55%	28.73%	35.27%	38.08%

Table 1: Error Estimates of TBHM and HWES Models

Based on MAPE values, it can be concluded that the 'non functional average trend' model is a reasonably accurate and inexpensive method of modeling short-term traffic flow data for urban signalized intersections. The effectiveness of the two models are judged by comparing the variation in the traffic volume prediction and simulation intervals from the HWES model and the TBHM model (for 12th and 13th July 2005) for both junctions TCS 183 and TCS 439.

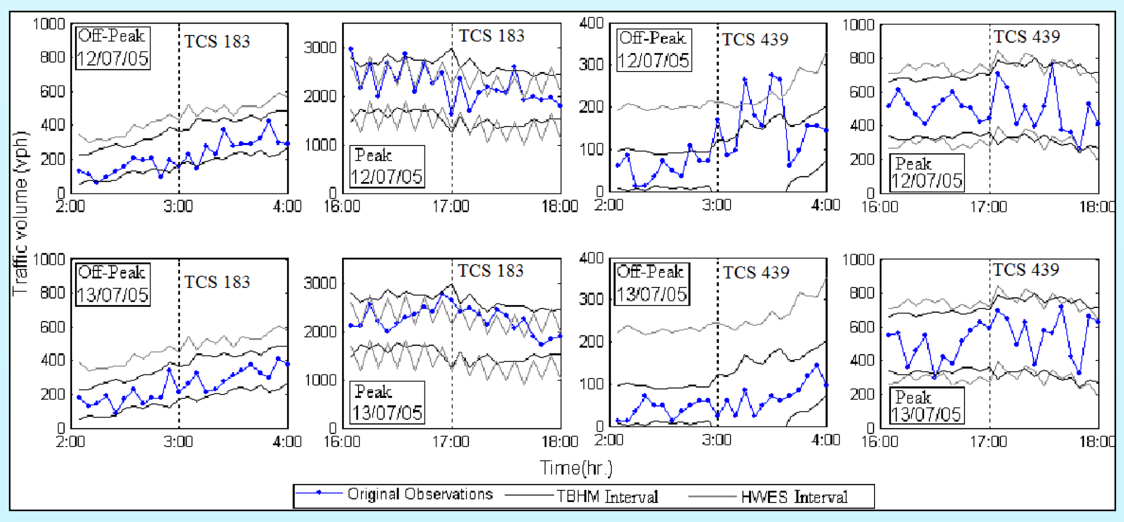


Figure 3: Simulation and Prediction Intervals from the TBHM and the HWES models for Traffic Volume at Junction TCS 439 and TCS 183

The simulation range obtained for traffic flow observations for both the junctions from the TBHM model varies with the time of the day (wider at peak hours and narrower at off-peak hours) unlike the constantly wide prediction interval from the HWES model. In all the off-peak hour graphs the HWES model fail to give any satisfactory lower limit of prediction. In general, the proposed TBHM model sets a tighter confidence interval to track the traffic volume variation as compared to the HWES model.

CONCLUSION

The proposed TBHM model can simulate a short-term traffic volume range over a day reasonably accurately without using any observations from current and/or recent past unlike all other existing short-term traffic flow forecasting algorithms. Examples involving 2 intersections in Dublin illustrate that the TBHM model with a time-varying confidence interval is more effective than the well-known HWES model. A useful application of the TBHM model can be modeling traffic flow observations at non-critical junctions as well as at critical junctions when the data collection systems are not functioning for a considerable period of time leading to lack or absence of data from recent past. The proposed model can be effective in such scenarios where the existing short-term traffic forecasting models may not be applicable at all.

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