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Hierarchical fuzzy rule-based system optimized with genetic algorithms for short term traffic congestion prediction

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ABSTRACT

Taking practical and effective traffic prediction and control measures to ease highway traffic congestion is a significant issue in the research field of Intelligent Transportation Systems (ITS). This paper develops a Hierarchical Fuzzy Rule-Based System (HFRBS) optimized by Genetic Algorithms (GAs) to develop an accurate and robust traffic congestion prediction system employing a large number of input variables. The proposed system reduces the size of the involved input variables and rule base while maintaining a high degree of accuracy. To achieve this, a hierarchical structure composed of FRBSs is optimized by a Steady-State GA, which combines variable selection and ranking, lateral tuning of the membership functions, and optimization of the rule base. We test the capability of the proposed approach on short term traffic congestion problems, as well as on benchmark datasets, and compare the outcomes with representative algorithms from the literature in inferring fuzzy rules, confirming the effectiveness of the proposed approach.

1. Introduction

Nowadays, traffic congestion on highways is a global issue: in fact, almost all of nations suffer from it, to varying degrees. Among other problems, it causes business losses due to increased travel time, requires increases in public infrastructure investment, and threatens urban environmental quality due to the extra emissions involved. It has been estimated by the Transport White Paper (March 2011) that the costs caused by congestion will increase by approximately 50% by 2050. For these reasons, traffic control to ease highway traffic congestion is a significant issue in the research field of Intelligent Transportation Systems (ITS).

Therefore, the prediction of traffic congestion is a vital component of ITS, which aims to influence travel behavior, improve mobility, and save energy. Traffic predictive information can be used either by drivers directly to avert potential traffic blocks, or by traffic management and control systems to ensure traffic flow.

Over the last decades, some of the most used algorithms for traffic forecasting have been based on the Kalman Filter (KF) (Jin et al., 2013; Okutani and Stephanedes, 1984) and the Autoregressive Integrated Moving Average (ARIMA) (Ahmed and Cook, 1979; Williams and Hoel, 2003). Although these methods have improved traffic modeling and prediction, there are still some shortcomings in dealing with predictions. For instance, KF tends to generate overestimation or underestimation that

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deteriorates the prediction accuracy when the traffic condition undergoes very significant changes; on the other hand, ARIMA mainly targets single variable time-series data, instead of using a richer dataset.

In studies with richer datasets (Dougherty and Cobbett, 1997; Samoili and Dumont, 2012; Stathopoulos and Karlaftis, 2003; Vlahogianni et al., 2008), traffic flow, occupancy and speed have been found suitable for predicting traffic conditions in the short run. In particular, the results in (Dougherty and Cobbett, 1997) indicate that the traffic flow and occupancy prediction accuracy was higher than the speed. Other studies like (Balke et al., 2005; Lin et al., 2002) imply either that predictions based on traffic flow are more reliable through information theory to analyse a subset of real data from Austin, Texas; or that the use of occupancy, which is proportional to density, is a better indicator of traffic condition (Lin et al., 2002). However, there are some other contradictory findings, where the speed was found to be favoured over flow and occupancy, because they are more efficient and meaningful for the users (Samoili and Dumont, 2012).

In general, four input variables suitable for capturing and predicting traffic conditions have dominated the literature: mainline flow, occupancy, speed, and ramp flow.

In recent years, several soft computing techniques have received much attention and enabled an encouraging level of performance for traffic prediction purposes. These techniques can be broadly classified into Support Vector Machines (SVM) (Sapankevych and Sankar, 2009; Wang and Shi, 2013; Wu et al., 2004), Neural Networks (NN) (Chan et al., 2012; Hodge et al., 2011; Karlaftis and Vlahogianni, 2011; Smith and Demetsky, 1994), Fuzzy Rule-Based Systems (FRBS) (Dimitriou et al., 2008; Zhang and Ye, 2008), and Genetic Algorithms (GA) (Abdulhai et al., 2002). Furthermore, combinations or hybridizations of these have brought about promising results, such as the genetic optimization of NN (Vlahogianni et al., 2005). There are some other studies like (Quek et al., 2006; Zheng et al., 2006).

Among these techniques, the large number of variables involved may produce inaccurate prediction on the part of SVMs, due to the choice of the appropriate kernel function for the practical problem Wang and Shi (2013). NN has obtained relatively better performance at traffic forecasting and has attracted more attention. However, the local optimum and generalization ability limit its effectiveness. The reason for this is that the synaptic weights and thresholds of NN are random and time-consuming to initialize (Hodge et al., 2011). In addition, their performance mainly lies on the training process, and is especially affected by a large number of data with high quality and defined parameters (Posawang et al., 2010).

Fuzzy logic (Zadeh, 1965) is usually adopted to deal with the complexity derived from traffic situations (Liu and Fei, 2010; Onieva et al., 2012). It allows processing uncertain information to be simply represented as simple rules, e.g. for the traffic congestion prediction problem. Traffic states, such as speed, occupancy and flow, are grouped into finite categories, such as high, medium, and low. Then, rules are created to relevant traffic states with congestion detection. For example, a rule can be: *if the occupancy is high, speed is low, and flow is medium, then congestion is positive*. Among Fuzzy Logic systems, FRBS is the most representative case, which has been applied in many kinds of complex real-world problems.

GAs are stochastic search algorithms, which are inspired by natural evolution principles of species in nature (Holland, 1992). GAs have often been used in the literature, since they can deal with extremely complex problems which are hard to solve by traditional methods (Konar, 2005). GAs have also been widely applied for FRBS learning and tuning. A number of papers have been dedicated to the automatic generation of the knowledge base of a FRBS (Badie, 2010). One of the most successful applications is Genetic FRBS (GFRBS), where a GA is used to learn or tune the components of a FRBS (Cordon et al., 2004; Onieva et al., 2012).

The design of a FRBS is generally a time consuming and complex process. It involves knowledge acquisition, the definition of the controller structure, the rules, and the other parameters. When a traditional FRBS is faced with a large scale problem (i.e., with a high number of input variables), the number of rules increases exponentially while the obtained FRBS is barely accurate or interpretable. Up to now, one of the most important issues in FRBS is how to reduce the size of the rule base involved while maintaining an adequate accuracy. One feasible way to achieve this goal is to arrange the input variables hierarchically, which is known as *hierarchical FRBS* (HFRBS) (Benítez and Casillas, 2013; Raju et al., 1991). HFRBS consists of a number of low-dimensional fuzzy systems arranged hierarchically. This way, the total number of rules grows only linearly with the number of input variables.

In order to implement these systems, several proposals have been presented (Benítez and Casillas, 2013; Cala and Moreno-Velo, 2010; Cordón et al., 2003; Lee et al., 2003; Stonier and Mohammadian, 2004). Some of them identify common parts of the set of rules and create submodules that generate these common parts (Cala and Moreno-Velo, 2010; Torra, 2002). In other schemas, the hierarchical level of each module refers to an increase in the granularity of the variables (Cordón et al., 2003). The authors in Lee et al. (2003) propose an approach of mapping rule-based schemes, referred to as a limpid-hierarchical fuzzy system, which aims at overcoming the problem that the outputs of the intermediate layers do not possess physical meaning. The work presented in Stonier and Mohammadian (2004) gives an introduction to hierarchical fuzzy control along with several examples by using evolutionary algorithms. The authors in Benítez and Casillas (2013) suggest the use of a multi-objective GA to learn HFRBS, especially dedicated to reducing the size of the rules and to improving the interpretability of the system. However, the curse of dimensionality is still an unsolved, and difficult, problem in fuzzy logic control theory (Zajaczkowski and Verma, 2010).

This paper is motivated by the circumstance that previous methods have their own advantages and disadvantages, and a particular previous approach may not be able to accurately predict traffic congestion with a high number of variables over the durations of the prediction period. For purpose of achieving more accurate and robust traffic prediction, we here propose a Genetic Hierarchical FRBS (GHFRBS) capable of predicting traffic congestion in multiple prediction horizons.

The original contributions of the proposal are as follows: