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Synergistic approaches to mobile intelligent transportation systems considering low penetration rate

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ABSTRACT

This paper investigates the effect of low penetration rate on mobile phone-based traffic state estimation (M-TES) models. Synergistic approaches, including an appropriate genetic algorithm (GA) based velocity–density estimation model and a notable artificial neural network (ANN) based prediction method for unacceptably low penetration rate, are proposed. The GA-based traffic state estimation model not only improves the effectiveness but also reduces the critical penetration rate required in the M-TES model. When the critical penetration rate is reduced the error-tolerance and the scalability of the estimation model can be significantly improved. The ANN-based prediction approach is introduced to overcome the weakness remaining in the GA-based traffic state estimation model when the penetration rate becomes unacceptably low or unknown. In addition, the effect of related road segments on the prediction effectiveness is thoroughly discussed. This work, therefore, provides practical instructions in narrowing the search space for finding prediction rules of the ANN model, thus improving the computational performance without compromising the prediction accuracy. The experimental evaluations confirm the effectiveness as well as the robustness of the proposed approaches. As a result, this research contributes to accelerating the realization of mobile phone-based intelligent transportation systems (M-ITS) or, of the M-TES systems in specific, since the essential issue of low penetration rate has been solved.

1. Introduction

Transportation [1] and road traffic [2] are important parts of any economy all over the world. Therefore, research in Intelligent Transportation Systems (ITS) [3,4] has attracted a numerous number of researchers in various fields including vehicular technology, transportation, civil engineering, statistical study, computational science, communication engineering, and so forth [5–7]. However, besides advanced achievements in ITS, traffic congestion still remains as a serious issue in almost every big city across the world. A traffic jam is not only the cause of economic loss but also the source of pollution (air, noise pollution, etc.), violence and other social issues [8,9]. The Urban Mobility Report [10] reported in 2007 that traffic congestion causes 4.2 billion hours of extra travel time requiring 2.9 billion extra gallons of fuel, which cost the United State tax-payers an additional $78 billion [11]. The Ministry of Land Infrastructure and Transport of Japan reported in 2006 that the economic loss caused by a traffic jam is around $100 billion annually [12]. In addition, the situations where ambulances are hopelessly stuck on the way to hospitals; shops along the road sides have to be closed; students, teachers, workers, officers cannot go to school/work in time because of traffic jams, are not unusual in the modern cities. Such uncomfortable and even dangerous traffic environments are declining the citizens' quality of life (QoL).

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Traffic state estimation is one of the most important fields in ITS researches [13,3] aiming at alleviating traffic congestion. Obviously, correct updated traffic information helps commuters to avoid unconsciously entering the heavy traffic areas so that traffic congestion can be avoided. A reliable traffic state estimation system must provide not only accurate but also real-time traffic state information at any place (ubiquity). Existing traffic state estimation systems mainly employed traditional data collection methods which relied on road-side fixed sensors such as loop detectors [14,15], RFID readers [16,17], video cameras [18], and so forth. These techniques, however, disclosed their essential weakness in terms of coverage limitation as well as investment cost since it is impractical to install a huge number of road-side fixed sensors on every street [19]. To solve these issues, mobile devices have been utilized as traffic probes to collect traffic data [20,21]. Since mobile phones are available everywhere and the mobile phone network has already been deployed, the issues of coverage limitation, real-time effect, investment and maintenance cost mentioned above can be overcome [22–24]. Consequently, the mobile phone based ITS (M-ITS) [25] research is entering a new stage aiming at realizing a SAFE and GREEN (no traffic congestion) traffic environment [26,27] to improve the citizens' QoL.

In spite of the aforementioned advantages, the *m*obile phone based *t*raffic state *es*timation (M-TES) approach faces several issues related to uncertain penetration rate [11,28,29]. The penetration rate is the fraction of the number of vehicles (i.e. the number of mobile phones carried by vehicles) that report data to the estimation server out of the total number of vehicles traveling through the considered road segment. Intuitively, the higher the penetration rate the more effective the system is. However, there is no way to compel each mobile phone user to report traffic data to the server. In addition, when the system has just been launched, the penetration rate is usually lower than the one required which significantly distorts the estimation's effectiveness. Therefore, the penetration rate issue is considered as an essential barrier of the M-ITS realization. This barrier should be removed by appropriate approaches ensuring traffic estimation accuracy even in cases of low penetration rate.

This paper investigates and proposes suitable solutions for the aforementioned penetration rate related issues. More concretely, the effect of low penetration rate on traffic state estimation effectiveness will be thoroughly investigated. According to this investigation, a notable genetic algorithm (GA) based velocity–density estimation model will be proposed. The proposed GA mechanism is expected not only to improve the traffic state estimation accuracy but also to minimize the *critical* penetration rate (the penetration rate at which the estimation accuracy is still good enough but it will drastically decrease if the penetration rate becomes lower). This approach enhances the reliability as well as the scalability of the estimation system. Moreover, a practical Artificial Neural Network (ANN) based prediction model is proposed to ensure the effectiveness of the M-TES model when the penetration rate becomes unacceptably low, namely just several percent or even 0%. Last but not least, the effect of different order/level related road segments on the prediction accuracy is investigated. As a result, the search space of the ANN-based prediction model can be minimized, thus improving the computational performance without compromising the prediction effectiveness.

This article is organized as follows: Section 2 reviews the related work revealing the necessity of this research. The problem formulation and related definitions are presented in Section 3. Section 4 introduces an appropriate GA-based mechanism to optimize the velocity–density inference model. The ANN-based prediction approach dealing with unacceptably low or unknown penetration rate is discussed in Section 5. This section also investigates the effect of different order related road segments on the prediction accuracy by which the search space for finding prediction rules in the ANN model can be reduced significantly without compromising the prediction effectiveness. The evaluations are thoroughly discussed in Section 6. Section 7 concludes this work and draws out future research directions.

2. Related work

From the past decade, several researches have been dedicated to utilizing mobile phones as traffic probes for traffic state estimation [30–32]. Although several types of sensors such as GPS, accelerometers, cameras, etc., have been equipped in commercialized mobile phones [33,34], not all of these sensors can be effectively utilized for traffic data collection due to the requirements of autonomy and invisibility of this system [35]. Consequently, traffic data a mobile phone can report to the estimation is primarily the GPS data which consists of time stamp (in seconds), position (longitude, latitude), current velocity, direction and vehicle ID of the vehicle that sent data. This data is useful in intelligent transportation related systems such as recognizing pedestrians [36], classifying vehicles [37], monitoring safe drives [38], estimating traffic state [39–41], and so forth. The mobile phone based approach, however, retains several issues which can be categorized as follows: (1) the limitations of the sensors equipped on the commercial ''on-the-shelf'' mobile phones [42,43]; (2) the limitations in the mobile phone technology resources such as the computational capacity of mobile phones and the bandwidth of the mobile phone network [44]; and (3) the difficulties rooted from low and uncertain penetration rate (the portion of the number of vehicles that report data to the estimation server out of the total number of vehicles traveling in the considered road segment) [45,46].

In 2008, a mobile phone based traffic state estimation project named Mobile Century Project was started in the University of California, Berkeley. This project was renamed Mobile Millennium Project (MMP) in 2010 [47] and is currently in its evaluating stage. Here, GPS enabled mobile phones are utilized as traffic probes for real-time data collection. The estimation server processes data, estimates traffic states, and disseminates traffic state information to drivers via a mobile phone network or via the Internet.