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Studying the benefits of carpooling in an urban area using automatic vehicle identification data

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ABSTRACT

Carpooling has been considered a solution for alleviating traffic congestion and reducing air pollution in cities. However, the quantification of the benefits of large-scale carpooling in urban areas remains a challenge due to insufficient travel trajectory data. In this study, a trajectory reconstruction method is proposed to capture vehicle trajectories based on citywide license plate recognition (LPR) data. Then, the prospects of large-scale carpooling in an urban area under two scenarios, namely, all vehicle travel demands under real-time carpooling condition and commuter vehicle travel demands under long-term carpooling condition, are evaluated by solving an integer programming model based on an updated longest common subsequence (LCS) algorithm. A maximum weight non-bipartite matching algorithm is introduced to find the optimal solution for the proposed model. Finally, road network trip volume reduction and travel speed improvement are estimated to measure the traffic benefits attributed to carpooling. This study is applied to a dataset that contains millions of LPR data recorded in Langfang, China for 1 week. Results demonstrate that under the real-time carpooling condition, the total trip volumes for different carpooling comfort levels decrease by 32–49%, and the peak-hour travel speeds on most road segments increase by 5–40%. The long-term carpooling relationship among commuter vehicles can reduce commuter trips by an average of 30% and 24% in the morning and evening peak hours, respectively, during workdays. This study shows the application potential and promotes the development of this vehicle travel mode.

1. Introduction

Carpooling, as one of the traffic demand management (TDM) strategies, has been considered an environment- and society-friendly means to solve several road traffic problems (Shaheen et al., 2016a). Consequently, many cities worldwide have implemented carpooling schemes (Handke and Jonuschat, 2013; Shewmake, 2012; Teal, 1987; Vanoutrive et al., 2012), and several smartphone applications (apps) have been developed to promote carpooling (Shaheen et al., 2016b). Researchers have focused on carpooling policy implementation (Wang, 2011), carpooling influencing factors (Buliung et al., 2012, 2010), carpooling efficiency enhancement (Dimitrakopoulos et al., 2012; Nourinejad and Roorda, 2016), and individual features under carpooling (Galland et al., 2014; Shaheen et al., 2016c).

However, the efficient implementation of carpooling has remained inconsistent since its introduction in the 1970s. A number of studies and surveys have reported that various factors influence the travel choice of carpoolers. Certain factors, such as high fuel prices (Bento et al., 2013), intention to save on travel cost (Correia and Viegas, 2011), and workplace TDM policies (Buliung et al.,

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2010), encourage carpooling. By contrast, other factors, such as the improper use of high-occupancy vehicle lanes (Giuliano et al., 1990; Li et al., 2007; Shewmake, 2012), additional time requirement, loss of privacy, and difficulty in finding a matching ride, impede the development of carpooling. During the 1980s and 1990s, the percentage of carpoolers among commuters decreased even if policies that promoted carpooling were implemented. Recently, smartphones have assisted carpoolers in finding a match by using real-time ride-matching apps (Abrahamse and Keall, 2012). These apps have recaptured the attention of travelers toward this travel mode. In the past 15 years, carpooling has expanded in terms of user scale and the development of carpooling should be finely planned (Cohen and Shaheen, 2016).

The benefits of carpooling on the traffic system should be elaborated first before its large-scale implementation. Through the development of traffic detection technology, this procedure can be implemented by using a massive travel trajectory dataset. Santi et al. (2014) used a dataset that contained millions of taxi trips to study the benefits of a taxi-sharing system in New York City. Their results showed that cumulative travel length could be cut by at least 40% using this system. Alonso-Mora et al. (2017) developed a large-scale real-time ride-sharing algorithm, which was validated through an experimental study using the dataset of New York City taxicabs. These researchers found that 98% of taxi demand could be satisfied by using only 2000 ride-sharing vehicles (equivalent to 15% of the taxi fleet) with a capacity of 10 and an average waiting time of 2.8 min. In the study of Ma et al. (2013), a ride-sharing taxi service in Beijing reduced the total travel distance of taxis by 13% compared with a taxi system that transports passengers individually when the ratio between the number of taxi queries and the number of taxis is 6. However, these evaluations remain on the traffic demand reduction stage, and only a few works have considered traffic benefits resulting from carpooling, such as travel time reduction and travel speed improvement.

The present work focuses on identifying the potential benefits of carpooling among existing vehicle travel demands based on a massive citywide dataset. This study is conducted under an ideal condition in which travelers are willing and have sufficient information and technical means to participate in carpooling without changing their travel trajectories. In this regard, vehicle trajectory reconstruction and the carpooling matching method should be prioritized.

The data used in trajectory reconstruction can be divided into two classes: (1) extrinsic mobility data, such as mobile phone check-in data, which cannot directly depict traffic mobility; and (2) intrinsic mobility data, such as those collected by a vehicle Global Positioning System (GPS), a smart card system, and a roadside traffic detection system, which are concerned directly with traffic activities (Zhao et al., 2018). Compared with extrinsic mobility data, intrinsic mobility data provide more abundant and accurate travel information for trajectory reconstruction. Zheng (2015) summarized the detailed procedures for trajectory reconstruction based on GPS data, including outlier detection, trajectory compression, trajectory section and map matching. Yu et al. (2018) reconstructed vehicle trajectory based on roadside license plate recognition (LPR) data by using the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method. Similarly, Yildirimoglu and Kim (2017) proposed a simple method to extract vehicle trajectory information from roadside Bluetooth detectors. These studies show the feasibility and superiority of trajectory reconstruction based on intrinsic mobility data.

A driver will only consider picking up and conveying a carpooler to a specific location if the additional time requirement is minimal. That is, for a driver, finding a potential carpooler is finding a traveler with a similar trajectory and time window. Evidently, this problem is a typical spatiotemporal trajectory similarity problem. Recent studies (Sakurai et al., 2005; Vlachos et al., 2002) have proposed various approaches to measure trajectory similarity between moving objects, and most of these studies have focused on free-moving trajectories. However, a car in a city can move only on road segments, which form a route-constrained network. Therefore, researchers have begun to focus on spatiotemporal trajectory similarity on road networks (Abrahamse and Keall, 2012; Hwang et al., 2005, 2006; Kim and Mahmassani, 2015). Various methods have been adopted to study the similarity between trajectories on road networks. Examples of these methods include the time-warping distance method and the one-way distance method (Lin and Su, 2008; Shim and Chang, 2003), the dissimilarity in length measurement (Won et al., 2009), methods based on the point and time of interest (Abrahamse and Keall, 2012; Hwang et al., 2006), and the longest common subsequence (LCS) (Kim and Mahmassani, 2015). Among these, LCS is a string-matching algorithm in which the longest common subsequence of all the sequences can be derived in a set of sequences (Bergroth et al., 2000). Thus, LCS can serve as the basis for a carpool matching algorithm. To maximize the benefits of carpooling in a traffic system, the current study also proposes an integer program model, through which the optimal carpool matching strategy can be determined. The proposed model can be efficiently solved by using the blossom matching algorithm (Edmonds, 1965, 2009) in a non-bipartite network transformed from the original integer program model.

Although previous studies have measured the outcomes of carpooling (Guidotti et al., 2017) or ride-sharing (Cici et al., 2014; Dong et al., 2018; Hong et al., 2017), the potential benefits addressed by researchers are merely trip reductions. The overall consideration of traffic condition improvement resulting from carpooling remains lacking. The trajectory data used in the previous studies are typically obtained from a portion of vehicle travelers in the research area, which leads to deviations when estimating the effects of carpooling. In the current study, citywide LPR data, which exactly preserve travel information in vehicle mode, will be reconstructed into vehicle trajectories. Then, a two-step method is proposed to search for potential carpooling trajectories on road networks based on spatiotemporal similarities. The first step is spatial filtering, which is based on an updated LCS algorithm for detecting spatial similarity. The second step is temporal filtering, which is based on the criterion defined in this study. Further, an integer programming model based on the updated LCS algorithm is used to obtain the optimal carpool matching strategy. Finally, the effect of traffic condition improvement is evaluated in this research. In addition, carpooling benefits will be evaluated under two scenarios: (1) all vehicle trajectories under real-time carpooling condition and (2) commuter vehicles under long-term carpooling condition. The major contribution of this work is the use of LPR data to evaluate the prospects of carpooling in different implementation complexities. To the best of our knowledge, this study is the first to propose a carpooling benefit evaluation approach from actual roadside detector data. The results will help guide the implementation of carpooling.