Novel dynamic formulations for real-time ride-sharing systems

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A R T I C L E   I N F O

Keywords:
Ride-sharing
Dynamic
Matching policy
Rolling horizon
Clustering

A B S T R A C T

This paper proposes new objective functions for the matching problem arising in ride-sharing systems based on trips' spatial attributes. Novel dynamic matching policies are then proposed to solve the problem dynamically in a rolling horizon framework. Finally, we present a new clustering heuristic to tackle instances with a large number of participants efficiently. We find that the proposed models maximize the matching rate while maintaining distance-savings at an acceptable level, which is an appealing achievement for ride-sharing systems. Further, our solution method is capable of solving large-scale instances in real-time.

1. Introduction

Travel cost, traffic congestion, limited capacity for car park and environmental concerns have continually encouraged people to shift their travel modes toward emerging alternatives. Ride-sharing is a promising and competitive approach to reduce private car ownership. In its original form, ride-sharing consists of picking-up riders along a trip incidental to the principal purpose of the driver. In this case, the driver intends to reach a destination and not to transport people just for profit (Code of Virginia, 1989).

It is widely acknowledged that ride-sharing may be able to meet the mobility needs of a significant share of the travellers (Stiglic et al., 2015). Smartphones have facilitated the development of ride-sharing systems by linking riders and drivers in a dynamic and on-demand environment. Hence, in modern ride-sharing systems, drivers and riders are matched automatically and both parties can be notified within short notice (Agatz et al., 2011; Gargiulo et al., 2015; Stiglic et al., 2016). Depending on the level of dynamism of the ride-sharing system, a trip notification can be sent anytime from a few hours to a few minutes before departure time.

Coordination mechanisms between drivers and riders, especially the matching problem therein, have been the focus of the research on ride-sharing models (Kamar and Horvitz, 2009). Improving system-wide and trip attributes such as the matching rate, total travel times, or total trip distances have been considerably studied in the literature. Further, for wide uptake and real-time applications, ride-sharing systems should be computationally scalable.

Due to their significant computational requirements, the majority of dynamic ride-sharing models are only applicable to small and medium scale problems, hence compromising their implementation over large metropolitan areas. For example, over 13.5 million trips are currently made in Melbourne on a daily basis. Assuming that only 0.5% of the travellers decide to opt for a ride-sharing solution, the existing solution methods are not capable of efficiently finding near-optimal solutions.

In this paper, we develop a real-time ride-sharing system that iteratively solves a matching problem in a rolling horizon approach. The matching problem solved therein is based on the formulation proposed by Agatz et al. (2011). We build on this research by proposing novel objective functions for the ride-sharing matching problem and comparing their performance against two alternative objectives. Further, we propose multiple dynamic matching policies to implement the proposed rolling horizon approach. Finally, we...
propose an efficient clustering approach to decompose the announcements issued by the participants into smaller subsets and show that this heuristic approach is competitive compared to an exact solution method.

The rest of the paper is structured as follows. The literature on ride-sharing optimization models is reviewed in Section 2. Section 3 formally presents the ride-sharing problem and its mathematical formulation. Section 4 presents a rolling horizon approach to solve the problem dynamically and introduces three classes of dynamic matching policies. In Section 5, we introduce a heuristic clustering algorithm to solve the ride-sharing problem on large-scale instances. Numerical results obtained from solving realistic instances derived from Melbourne's metropolitan area are presented in Section 6. Finally, our findings and possible extensions are summarized in Section 7.

2. Literature review

In this section, we review the existing research on ride-sharing models. We then discuss the performance measures used for evaluating ride-sharing systems.

2.1. Ride-sharing models

Ride-sharing models have recently received an increasing attention in the literature. The proposed models differ in their approach to solve the optimization problem as well as in the level of input data required. Amey (2011) proposes a data-driven methodology for estimating the viability of ride-sharing at an institutional scale, the MIT campus in Cambridge, Massachusetts, USA. Given commuter-specific trip characteristics (housing location, vehicle availability, arrival/departure time and route deviation time), the author compares the potential of using ride-sharing as a travel mode based on observed trip characteristics and ridesharing patterns among commuters. In this study, the optimization problem seeks to maximize the number of matched driver-rider pairs and must decide on both the role assignment (driver or rider) to each participant and the assignment of riders to drivers. This study shows a potential system-wide vehicle miles travelled savings from 9% to up to 27%.

Agatz et al. (2011) utilize a rolling horizon solution approach to periodically optimize unmatched announcements. At each iteration of the rolling horizon, a matching problem is solved with an objective function aiming to maximize the total travel distance savings. In this model, the system is allowed to delay trip notifications until departure time. This leads to notifications often being postponed as late as possible. The authors use the Bass diffusion model (Mahajan et al., 1995) to model the adoption and the sustainability of the proposed dynamic ride-sharing system. The diffusion model contains three parameters: the total number of potential adopters, a coefficient of innovation that represents the exogenous likelihood that a new participant joins the system, and a coefficient of imitation that relates to the increase in this likelihood based on the number of participants that are already in the system. They report that when innovation and imitation rates are sufficiently high, the proposed ride-sharing system converges to a steady announcement stream in two to three weeks. As in Amey (2011), the system assigns participants' role, i.e. driver or driver.

Xing et al. (2009) introduce a dynamic ride-sharing system where drivers and riders are matched en-route. Trip preferences such as gender and smoking as well as a maximum acceptable service response time for riders are included in their model. They investigate the relationship between the number of drivers and passengers' travel time. Using a simulation-based experiment on an urban network of Bremen's metropolitan area, the authors find that increasing the number of available drivers results in higher matching rates.

Stiglic et al. (2015) design an algorithm that matches drivers and riders in a ride-sharing system with meeting points. Meeting points increase the flexibility of the ride-sharing system by expanding the set of feasible matches. They consider two objective functions in a lexicographic optimization approach: their primary objective is to maximize the total number of matches while their secondary objective aims to maximize the total travel distance savings. In line with addressing the impact of participants' flexibility, Stiglic et al. (2016) use the same model to investigate the impact of matching flexibility, detour flexibility, and scheduling flexibility on matching rates.

Ghoseiri et al. (2011) formulate a ride-sharing problem in which several constraints for vehicle occupancy, waiting time to pick up, the number of connections, detour distance for vehicles and relocation distance for passengers are considered. In addition, trip preferences based on age, gender, smoking, and pet restrictions are incorporated. As in most approaches, the authors maximize the number of matches.

In a recently published paper by Masoud et al. (2017), a peer-to-peer ride exchange mechanism is proposed to increase the matching rate and customer retention in a ride-sharing system. In the mechanism, riders have the opportunity to purchase a previously-matched rider's itinerary while the exchange of rides is accompanied with an exchange of money through the ride-sharing system. For a more comprehensive review on the state of the art of current ride-sharing systems and the existing challenges to their adoption, the reader is referred to Furuhata et al. (2013).

In this paper, we build on the existing literature and propose new objective functions for the matching sub-problem arising in the dynamic ride-sharing problem. In addition, we introduce three classes of dynamic matching policies for the rolling horizon framework that provide a range of trip notification deadlines.

2.2. Large-scale solution approaches

One of the main challenges of dynamic ride-sharing is to deal with a large number of participants and some heuristics have been proposed to develop scalable solutions. Shen et al. (2015) use a Filter-and-Refine framework to scale down the ride-sharing problem. In their framework, the road network is first partitioned using a grid and driver and rider requests are then filtered based on a spatio-temporal index. Pelzer et al. (2015) partition the road network into distinct regions representing certain sub-structures of the road.
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