Computers and Operations Research 81 (2017) 40–50

Contents lists available at ScienceDirect

Computers and Operations Research

journal homepage: www.elsevier.com/locate/cor

Minimizing CO_2 emissions in a practical daily carpooling problem

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A R T I C L E I N F O

Article history:
Received 9 November 2015
Revised 31 July 2016
Accepted 2 December 2016
Available online 8 December 2016

Keywords:
Carpooling
Ridesharing
Vehicle routing
CO_2 emissions

A B S T R A C T

Governments, as well as companies and individuals, are increasingly aware of the damages to the environment caused by human activities. In this sense, the reduction of CO_2 emissions is an important topic that is pursued through a range of practices. A relevant example is carpooling, which is defined as the act of individuals sharing a single car. In this paper we approach a practical case found in an Italian service company. Our objective is to develop an integrated web application to be used by the employees of this company to organize carpooling crews on a daily basis, so as to reach a common destination. We look for possible crews by the use of mathematical formulations and heuristic algorithms. The heuristic algorithms are then embedded into the web application to provide users with carpooling solutions. Experimental results attest for a great potential in CO_2 savings by the use of carpooling in the real-world scenario as well as in newly generated instances.

1. Introduction

The debate on the negative effects of human activities on the environment has been around for a long time, and nowadays the concern about these issues is widespread. Pollution is a plague in urban areas and a cause of illness for inhabitants. Large companies daily require that thousands of individuals travel to work, heavily increasing car use. This practice causes a wide range of problems, including high emissions of CO_2 in the atmosphere, noise pollution, and parking issues (see, e.g., Gärling and Friman [1]). Public transportation systems could mitigate the problem, but, more often than not, they are incapable of serving all the demands in a cost-effective manner, or are simply disregarded by many individuals, who prefer not to use them.

In this sense, *carpooling* can be an effective tool to help reduce traffic and pollution. Carpooling is a ridesharing practice that can be defined as the act of a group of individuals that ride a single car by splitting travel costs (see, e.g., Furuhata et al. [2]). This practice has grown more common in recent years. It is an interesting transportation habit for individuals as well as for companies, as it can reduce transportation costs and directly affect CO_2 emissions. It thus fits well with the millennium goal of the United Nations [3] that aims at ensuring environmental sustainability. Governments are also taking actions to support the carpooling practice. For instance, in Italy a law for sustainable mobility was included into the national legislation in 1998 to stimulate the use of collective transportation methods and promote the creation of innovative transport systems (see Italian Ministry of Environment [4]). Consequently, in recent years several optimization methods have been developed to provide good solutions to different carpooling practices, both focusing on the solution of real-world study cases (see, e.g., Wolfler Calvo et al. [5]) and on the development of general solution algorithms (see, e.g., Baldacci et al. [6]).

Carpooling is sometimes also denoted as *ridesharing*, although this terminology is more common in dynamic contexts (see, e.g., Agatz et al. [7,8]). Also, it should not be confused with *carsharing*, which is a kind of decentralized car rental service where travelers are allowed to pick up a car at a station, use it for the time needed, and then return it (to the same station or to a different one, according to the implemented system). Carsharing has also attracted research aimed at the minimization of CO_2 emissions. Lee et al. [9] pursued indeed this objective by determining the optimal carsharing service locations in Daejeon, a small Korean city. The reader interested in the research conducted on carsharing is referred to the recent survey by Jorge and Correia [10].

In this paper we focus our attention on carpooling and study a practical case found in a large service company, Coopservice S.coop.P.A., with headquarters in Reggio Emilia (Italy), whose aim is to encourage its employees to carpool to reduce transportation costs and CO_2 emissions. We focus on a pilot case in which all employees are headed to the same workplace but may have different daily working shifts. People with the same shift can carpool together to reach and/or return from the workplace at the same

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http://dx.doi.org/10.1016/j.cor.2016.12.003
0305-0548/

time. According to the classification by Wolfler Calvo et al. [5] our case is a *daily* carpooling problem, because users offer or require passages on the basis of working shifts that change day by day. Our intention is to assess, by the use of optimization algorithms and mathematical models, the amount of CO_2 emissions that can be saved in this pilot case and on newly generated instances, and then develop a web application in which employees can communicate and agree with each other on sharing rides.

The remainder of the paper is organized as follows. In Section 2 we present a brief review of the carpooling literature. In Section 3 we formally describe the problem. In Section 4 we present mathematical models and heuristic algorithms. In Section 5 we discuss the details of our study case. In Section 6 we evaluate our optimization methods by means of extensive computational results. In Section 7 a prototype of the web application is shown and then some conclusions are drawn in Section 8.

2. Brief review of carpooling literature

The practice of carpooling (also known as ridesharing) has attracted the interest of many researchers from different areas, consequently leading to a huge literature. In this section we present a brief review of some interesting results in the field. The reader interested in a deeper review is referred to the following papers: Furuhata et al. [2], who present a framework to identify key challenges in ridesharing and foster the development of effective formal ridesharing mechanisms; Chan and Shaheen [11], that focus on how the use of Internet, mobile phones, and social networking has been integrated in carpooling programs; Battarra et al. [12] and Dörner and Salazar-González [13], that survey pickup and delivery problems for freight and passenger transportation, respectively.

The carpooling literature can be roughly divided into two major approaches: a *deductive* approach and an *inductive* one. The former approach looks at carpooling through the lenses of existing literature from different research areas, and thus tries to apply existing theories (deriving from fields such as behavioral theories and applied psychology) to draw conclusions on the usage and effectiveness of possible practical carpooling systems. From this perspective, deductive studies share a somehow top-down approach. Instead, the latter approach examines existing carpooling initiatives in order to understand what correlations among variables arise in real contexts, or what individuals think that might lead them to carpool. In this sense, inductive studies start from reality and try to draw general conclusions about the carpooling phenomenon, thus sharing a bottom-up approach.

The main results on deductive and inductive approaches are surveyed in Sections 2.1 and 2.2, respectively, whereas in Section 2.3 we describe the main models and algorithms that have been developed to provide optimized solutions to carpooling problems.

2.1. The deductive approach

The deductive approach roughly follows the call of Gärling and Schuitema [14] for a behavioral framework able to help policy makers and carpooling system designers to develop effective car use reduction programs, as well as to support individuals to develop their own car use reduction goals. Gardner and Abraham [15] proposed an analysis of the literature on psychological correlates of car use with data taken from fourteen previous studies. Their research aim was to verify the impact of the *theory of planned behavior* (TPB) by Ajzen [16] on car reduction behavior. TPB is an expectancy-value theory in which the subjective perception of the probability of happening of a given behavior directly influences the process of creation of attitudes towards that behavior. Following [15], Abrahamse et al. [17] measured the impact of TPB and of the *norm-activation theory* (NAT) by Schwarz [18] on sample data from Canadian workers. While TPB looks at the mechanism through which behavioral intentions are formed, NAT is more about moral issues, i.e., about how problem awareness and perceived responsibility for consequences may modify individual attitudes towards a certain behavior. The authors highlight that individuals' attitudes and the perceived possibilities and difficulties related to reducing car use strongly influence the transportation choice.

Bamberg et al. [19] also considered TPB and NAT. They proposed and tested a conjoint self-regulation theory asserting that changes in behavior are a process of transition through successive stages. In particular, in the case of a car use reduction goal, the theory starts from the formation of the goal, then it passes through the formation of the behavioral intention to do it, and lastly it comes to choosing the alternative travel option that reduces car use. Shewmake [20] reviewed studies on the impacts of *high occupancy vehicle* lanes on carpooling, with a focus on behavioral models. Different performance measures related to welfare, congestion, and air pollution effects were surveyed, by taking into consideration papers that explicitly model carpool formation. In conclusion, behavioral theories seem to indicate that, in order to foster mixed transportation methods, both personal interest variables (e.g., the perception of alternatives), as well as personal norms should be taken into account when proposing carpooling systems.

Other important contributions derive from proposals of new models for web or app-based carpooling systems. These models try to devise carpooling systems by taking into account both contributions from the literature and from practical experiences, considering different perspectives such as social, technical, and business sustainability. Selker and Saphir [21] proposed a carpooling system that takes into account individual interests, goals, and preferences. They argued that having the same interests can reduce some negative psychological drawbacks of carpooling, as, for instance, privacy issues. They also conducted a promising pilot test within a university setting. Chen and Hsu [22] extended the model in [21], by defining other options aimed at improving the carpooling application. Ribeiro et al. [23] developed a web and app-based carpooling system, whose design benefits from an analysis of existing carpooling systems. Other web applications, more focused on optimization aspects, are discussed in Section 2.3.

2.2. The inductive approach

Governments and private organizations have created several travel plans to reduce environmental costs. This has provided researchers with the opportunity to go into the field and study existing applications. In what we call inductive studies, the authors analyzed existing carpooling initiatives and assessed whether and why individuals decided to participate.

In the United Kingdom, Cairns et al. [24] analyzed the efficacy of the travel plans of twenty employers. Their findings show that the presence of travel plans, in conjunction with parking management techniques, is capable of reducing car use. They also show that this practice can offer positive economic returns for the proposing companies because of the reduction in car parking requirements.

In Belgium, Vanoutrive et al. [25] studied commuters' choices by clustering individuals by company. This strategy is grounded on three arguments: employers can foster internal commutation patterns among employees; neighbor companies can have different accessibility options; companies are social settings where organizational culture and social norms can exert a great influence on the individual choice to commute. The authors found that carpooling initiatives could be effective only where public transportation