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Transportation Research Procedia 27 (2017) 736–743

Transportation Research Procedia

www.elsevier.com/locate/procedia

20th EURO Working Group on Transportation Meeting, EWGT 2017, 4-6 September 2017, Budapest, Hungary

An optimization model for vehicle routing of automated taxi trips with dynamic travel times

Xiao Liang[a,*], Gonçalo Homem de Almeida Correia[a] and Bart van Arem[a]

[a] *Department of Transport & Planning, Delft University of Technology, Stevinweg 1, Delft 2628CN, The Netherlands*

Abstract

In this paper, we propose a method of automated vehicle operation in taxi systems that addresses the problem of associating trips to automated taxis (ATs) and assigning those vehicles to paths on an urban road network. This system is envisioned to provide a transport service within a city area with a seamless door-to-door connection for all passengers' origins and destinations. ATs can drive themselves on the roads with reduced direct human input, which allow taxis to satisfy the next trip or park themselves while waiting for a request if needed. We propose an integer programming model to define the routing of the vehicles according to a profit maximization function while depending on dynamic travel times which vary with the flow of the ATs. This will be especially important when the number of automated vehicles circulating on the roads is so high that will cause traffic congestion. The total profit involves the system revenue, vehicle fuel costs, vehicle depreciation costs, parking costs, penalties for unsatisfied trips and passengers' congestion delay. The model is applied to a small case study and the results allow assessing the impact of the ATs movements on traffic congestion and the profitability of the system. Even with a small case study, it is possible to conclude that having in consideration the effect of the vehicle flows on travel time leads to different results in terms of the system profit, the parking cost and the driving distance which points out the importance of this type of models.

Peer-review under responsibility of the scientific committee of the 20th EURO Working Group on Transportation Meeting.

Keywords: Automated vehicles; Taxis; Vehicle routing; Dynamic travel time

* Corresponding author. Tel.: +31 (15) 27 85279.
E-mail address: x.liang@tudelft.nl

Peer-review under responsibility of the scientific committee of the 20th EURO Working Group on Transportation Meeting.
10.1016/j.trpro.2017.12.045

1. Introduction

In the recent years, technology development has accelerated the process of vehicle automation. This technology is expected to have a beneficial impact on travel efficiency, especially on interurban roads. With respect to the impacts of these vehicles, studies have used micro-simulation tools or mathematical models to estimate the changes in road capacity and congestion under different levels of vehicle automation and cooperation. (Arem et al., 2006; Bose and Ioannou, 2003; Calvert et al., 2011).

Regarding the use of automated vehicles as transit systems, there are currently many projects which are testing the use of automated pods or buses in pilot experiments. One of the most relevant example being the CityMobil2 project (CityMobil2, n.d.) in which several field experiments are being run in Europe to test the possibilities of automated bus systems. In 2015 the province of Gelderland in the Netherlands started developing a project named WEpods with two self-driving vehicles, which are used between the Wageningen University and the train station (WEpods, 2015).

Several approaches have been proposed to test the effect of transit automation on mobility, especially looking at the combination between traditional taxis and shared use taxi fleets. The automated taxis (ATs) may provide a new type of door-to-door service competing with the traditional taxis or even the public transport because these new systems would be able to avoid extra manpower costs and make the AT service cheaper. Fagnant & Kockelman (2014) used a simulation method to study the implications of shared ATs and described the results of a case-study application. The results indicate that each shared automated vehicle can replace around 11 conventional ones, with up to 10% more travel distance. The International Transport Forum (ITF) built a model to test the introduction of 100% autonomous fleets of taxis to satisfy transport demand in a city (International Transport Forum, 2015). Results showed that with the subway still in operation each automated vehicle could remove 9 out of 10 cars, whilst without metro, the number goes down to 5. Spieser et al. (2014) used an analytical mathematical formulation to estimate the number of shared automated vehicles to replace all modes of personal transportation in the case-study city of Singapore. Using actual data, they are able to conclude that a shared-vehicle mobility solution could meet the personal mobility needs of the entire population with 1/3 of the number of passenger vehicles currently in operation.

A recent study addressed the traffic assignment of privately owned automated vehicles from user optimum perspective with the objective of minimizing each family's own transport costs (Correia and van Arem, 2016). This model proposed an equilibrium convergence where households with similar trips should have similar transport costs. Since system optimum vehicle assignment is a nonlinear problem which is difficult to solve, this was tackled by an iterative process where travel times do not change during each assignment of vehicles to trips.

In this paper, we are going to study a transport system with a fleet of automated vehicles used as taxis which provide a transport service within a city area with a seamless door-to-door connection for passengers' origins and destinations. Then a model is proposed to address the problem of assigning the vehicles to paths on an urban road network while satisfying the demand. Moreover, this model is expected to solve the problem with dynamic travel times which vary with the flow of the ATs.

2. Mathematical model

In this section, we describe a linear programming model whose objective is to determine the optimal vehicle routing of the AT system. We consider a private taxi service between any pair of nodes within the city road network, with no background traffic flow which means the flow is generated only by the ATs themselves. Clients use an online app to book an AT with the travel information including the origin, the destination and the desired departure time. The model works on the assumption that the taxi company can achieve total control of the system by being free to accept or reject requests according to a profit maximization objective.

Sets:

$\boldsymbol{N} = \{1, \dots, i, \dots N\}$: set of the nodes in the network, where N is the total number of nodes.
$\boldsymbol{T} = \{0, \dots, t, \dots, T\}$: set of time instants in the service period, where T is the total number of time steps in the service period.
$\boldsymbol{T'} = \{-T^r, \dots 0, \dots, t, \dots, T, \dots, T + T^r\}$: set of time instants in the operation time, including the service period