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# Optimizing the service area and trip selection of an electric automated taxi system used for the last mile of train trips

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ABSTRACT

We propose two integer programming models for optimizing an automated taxi (AT) system for last mile of train trips. Model S1: trip reservations are accepted or rejected by the operator according to the profit maximization; model S2: any reservation on a selected zone by the model must be satisfied. Models were applied to a case-study. Results indicate that fleet size influences the profitability of the taxi system: a fleet of 40 ATs is optimal in S1 and 60 ATs in S2. Having electric ATs constrains the system for small fleets because ATs will not have time for charging.



## 1. Introduction

Within the last decade, technology development has accelerated the process of vehicle automation. An automated vehicle (AV), also known as a driverless car and a self-driving car is an advanced type of vehicle which can drive itself on existing roads and can navigate many types of roadways and environmental contexts with reduced direct human input (Fagnant and Kockelman, 2013). SAE International identifies six levels of driving automation from level 0 “no automation” to level 5 “full automation” (SAE International, 2014). Fully AVs are expected to bring significant benefits, such as mitigating traffic congestion, reducing car crashes, improving fuel efficiency and alleviation the negative impacts on environment (Bierstadt et al., 2014). Although further evidence is still needed to assess if those advantages are indeed real.

In recent years, most of the effort has been put into the technology challenges of creating fully AVs. Google has driven more than one million miles on public streets under autonomous mode since 2009 and is planning to make these cars available to the public in 2020 (Google, 2015). In addition to this, many automobile manufactures like General Motor, Mercedes-Benz, Audi, Nissan, BMW, Renault all expect to sell vehicles which can drive themselves by 2020.

With respect to the impacts of these vehicles on mobility, it has mainly focused on traffic impacts under different driving and infrastructure conditions. Most of these studies use micro-simulation tools or mathematical analysis to estimate the changes in road capacity and congestion under different levels of vehicle automation and cooperation (Bose and Ioannou, 2003; Calvert et al., 2011; van Arem et al., 2006).

Regarding the use of AVs as transit systems, physical trials have been the most relevant method of study so far. Automation in transit is not new, and there are currently many tram and metro lines operating without a driver in cities like Paris or Barcelona. Moreover automation is the basis for the so called Personal Rapid Transit (PRT) system. This is a flexible door-to-door public transport with small capacity vehicles which have their own dedicated infrastructure (Juster and Schonfeld, 2013). There are several examples in the world of its application but probably one of the most well-known is the case of

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London Heathrow Airport, the ULTra (Urban Light Transit). Based on these notions combined with the recent development of vehicle automation there are several projects which are testing, in pilot experiments, the use of automated road transit systems. One of the most notable is the CityMobil2 project (CityMobil2 – Cities demonstrating Automated Road Passenger Transport, n.d.; Csepinszky et al., 2014) 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 is developing a project named WEpods with two self-driving vehicles, which are used between Ede/Wageningen railway station and Wageningen University & Research Center (WEpods project DAVI – Dutch Automated Vehicle Initiative, n.d.). These are key experiments to test the technology but also the sensitivity of travellers to its characteristics, such as demand responsiveness or the absence of a driver. Nevertheless little has been done regarding the planning and operation of future transit systems constituted by AVs. Winter et al. (2016) use the case study of the WEpods project in the Netherlands to establish a method to dimension a fleet of automated buses, but these are only shadowing the existing bus line.

The most related research to our topic is looking at the combination between traditional taxis and carsharing (a short term rental of a vehicle that the traveller will drive himself) (Martin et al., 2010; Shaheen et al., 1999): with the advent of automation, the use of AVs in carsharing services may provide a new type of door-to-door service, competing with the traditional taxis or even shared taxi services such as Uber (Martinez et al., 2015) because these new systems will be able to avoid extra human costs associated with both traditional taxis and carsharing. Carsharing systems generate the problem of vehicle imbalance due to the one-way nature of the trips (Correia and Antunes, 2012; Jorge and Correia, 2013; Jorge et al., 2014; Kek et al., 2009) however, in the case of AVs, it is possible to do the relocation with lower costs between different areas because there is no need for a driver.

Fagnant and Kockelman (2014) proposed a simulation method to study the implications of shared ATs. They used an agent-based model for system operations and described the results of a case-study application where AVs were compared to conventional vehicle ownership and use. Their results indicate that each shared AV can replace around 11 conventional vehicles, but adds up to 10% more travel distance. Using the same technique, 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 show that fleets always decrease: with the subway still in operation each AV could remove 9 out of 10 cars in the city if a maximum 5 min waiting time is to be guaranteed, whilst without metro the number stays in 5 vehicles removed per AV.

In this work we do not study the full substitution of traditional transit networks but propose instead to analyze the potential of using automated taxis (ATs) as a last mile connection of train trips. Given parking space availability, a properly functioning road infrastructure and smooth traffic, the use of the private automobile is highly attractive especially at longer distances (Ford, 2012). Moreover in multimodal trips it has been shown that a relatively high disutility is caused by the access and egress modes of transport (Hess, 2009; Hoogendoorn-Lanser et al., 2006). At the same time, to make transport more efficient, concentrating passengers in higher capacity vehicles such as trains leads to cost and pollution savings, hence the use of fully automated electric vehicles to feed these higher capacity systems in a seamless way may be a good solution to bring more people to public transport and improve transport sustainability. The use of AVs for the first/last mile connection has been analyzed before but mainly on a technology perspective (Chong et al., 2011).

In this paper, we present an optimization approach to define the service area of an AT system which satisfies passengers' requests to access or egress a train station, in order to maximize the profit of the AT system. Since AVs can be relocated at a lower cost (no need to hire staff), the model considers the possibility of the vehicles travelling alone as a relocation method. Moreover the system is based on mandatory pre-booking, allowing accepting or rejecting demand according to the profit maximization function. From a methodological point of view the models are based on the ones by Correia and Antunes (2012), hence this paper contributes to the literature by introducing a novel application of these formulations to the case where automated vehicles are used, thus avoiding the high costs that today the traditional carsharing operators have to consider.

A zoning problem is by definition a planning problem, however to select trips is typically an operational problem which should be solved on a daily basis. In this paper we assume that our models are used on a daily basis for trip selection (operational purpose), but by running them with simulated trips for several replications before implementing the system we are able to obtain the zones which should be included in the service area around the station.

The paper is organized as follows. In Section 2 we introduce the mathematical models for two different trip selection schemes. Section 3 applies the models to the case study of the Delft Zuid train station in the city of Delft (the Netherlands). Finally a discussion on the results and main conclusions drawn from the model application are presented in Section 4.

## 2. Mathematical models

In this section, we describe the formulation of two integer programming (IP) models in order to determine the optimal service area and trips to be served by an AT system. The two formulations depend on how trips are selected from the total number of reservations done in one typical day (24 h in advance booking).

The first scheme (S1) is called free service. The model works in the assumption that the taxi company can achieve total control over trip selection, by being free to accept or reject requests according to the profit maximization. Waiting time is not applicable for the passengers since the trip is only served exactly at the starting time of the request. The model allocates each AT to a specific trip only if it will bring a higher daily profit. Otherwise, this request will be rejected with no extra penalty,