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Performance analysis and fleet requirements of automated demand-responsive transport systems as an urban public transport service

Konstanze Winter *, Oded Cats, Gonçalo Correia, Bart van Arem

Department of Transport and Planning, Faculty of Civil Engineering and Geosciences, Delft University of Technology, P.O. Box 5048, 2600 GA Delft, The Netherlands

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A B S T R A C T

The introduction of public transport services by fully automated vehicles can potentially change the way public transit services will be operated, as they allow shifting from rigid scheduled and route-bound services towards flexible, demand-responsive services. This study examines the potential performance of an *Automated Demand Responsive Transport Service* (ADRTS) as a replacement for scheduled bus services and simulates the effects of demand levels, vehicle capacity, vehicle dwell time and the initial vehicle distribution on system performance in terms of fleet size and system costs. The simulation tool allows simulating the operation of the ADRTS in a complete graph and is applied to the case study of Arnhem, the Netherlands. For this case study it has been shown that for a minimum fleet size following the imposed constraints, the operational costs range between 0.84 and 1.22 Euros and the average passenger wait time ranges between 2 and 6 min, according to the assumptions made on demand and operational parameters. The operational costs of the ADRTS showed to be in the same range of the current bus system, while providing a demand-responsive transport service with an average waiting time of around 4 min per passenger-trip. The economies of scale, which play an important role in public transport, are also apparent in the simulated ADRTS operations.

1. Introduction

The development of automated driving technology advances rapidly and automated vehicles (AVs) are commonly assumed to play a significant role in transport systems of the future (Alessandrini et al., 2015; Benevolo et al., 2016; Correia et al., 2016; Lam, 2015; Wang, 2015). The advancement of AVs potentially poses both opportunities and threats to conventional public transport systems. On one hand, if AVs rapidly enter the private car market, offering greater comfort and potentially productive travel time, public transport ridership may decline leading to efficiency losses. On the other hand, AVs pave the way for significantly reducing the operational costs of public transport services which are often dominated by driver labour costs. Moreover, the introduction of AVs into public transport services have the potential to revolutionize the way in which public transport services are provisioned and consumed by facilitating a shift into more flexible and demand

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* Corresponding author.
E-mail addresses: m.k.e.winter@tudelft.nl (K. Winter), o.cats@tudelft.nl (O. Cats), g.correia@tudelft.nl (G. Correia), b.vanarem@tudelft.nl (B. van Arem).

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responsive modes of operations. Conventional public transport systems offer scheduled services in rigid networks, in which passengers have to adjust their travel plans accordingly.

In this paper we envision an *Automated Demand Responsive Transport System* (ADRTS) which dynamically responds to travel requests using a centrally dispatched fleet of highly automated vehicles. The flexible and lower-capacity service enabled by ADRTS can potentially substitute conventional public transport in networks characterized by low to moderate levels of many-to-many demand pattern and where labour costs make the network-wide provision of DRT services prohibitive. Hitherto, demand-responsive services have proven to be exceptionally cost-intensive and therefore not economically viable beyond very low-demand or except for premium services, and usually require exceptionally high subsidy levels in developed countries which are characterized by high labour costs (Ferreira et al., 2007; Fu, 2002; Sayarshad and Chow, 2015).

The operation of an ADRTS is evaluated using a simulation model that allows assessing operator and passenger costs under alternative system specifications and scenarios. The main contributions of this study are: (1) determining the fleet size that will minimize ADRTS system (i.e. passenger and operational) costs under given constraints on maximum passenger waiting time; (2) determine the minimum fleet size for operating an ADRTS as a substitute to current public transport, and; (3) benchmark the passenger and operational costs to the existing bus system as well as a non-automated DRT system. To the best of our knowledge, ADRTS have not been modelled as a substitution for an existing urban public transport network. Previous studies have either assumed ADRTS to serve all demand for mobility and offer a door-to-door service (i.e. automated taxi) or considered a single corridor or feeder service operations.

The ADRTS is simulated for a case study based on the city of Arnhem in the Netherlands, for which the influence of demand, vehicle capacity, vehicle dwell time and the initial vehicle location on the system performance is analysed in terms of operational costs as well passenger generalized travel costs. Given the novelty of AV, assumptions made on the operational and cost parameters are of a speculative nature and the results presented in this paper should be therefore viewed as a first glimpse on the impact the introduction of AV might have on public transit services.

The paper is organized as follows: In Section 2, we review the automated public transport landscape with respect to emerging mobility solutions, taxonomy of ADRTS and the literature on modelling ADRTS. In Section 3, the ARDTS envisioned in this study is described along with the approach adopted in this study for modelling its operations. The case study and the scenario design are described in Section 4, followed by the results. We conclude with a discussion of the results, the limitations of the study and suggestions for further research.

2. The automated public transport front

2.1. Emerging new mobility solutions

In the last decade, new technological and societal mobility trends emerged, which could be potential game changers for both private and public transport. These trends include the advancement of vehicle automation, the rise of shared economy and growing urbanization which constitute important features in the portrait of so-called smart cities. At the time writing, technology is not yet mature enough to allow the deployment of such full-scale systems. However, current trends suggest that this may be a reality in the coming decade where planning and operational principles for such systems are still lacking. Pilot studies and trials worldwide have shown that automated vehicles (AVs) of all levels are operational and fully automated vehicles are expected to become part of the vehicle fleet in the not so distant future (Alessandrini et al., 2015).

Experiences with automated mass transit, sharing the infrastructure with non-automated vehicles and having limited guidance, have also been tested in several pioneering pilot studies (Alessandrini et al., 2014; Anderson et al., 2014; Christie et al., 2015; ERTRAC (European Road Transport Research Advisory Council), 2015; Fagnant and Kockelman, 2015; WEpods, 2016). These pilot trials operated single line connections between pre-determined pick-up and drop-off nodes. Such experiments are necessary not merely for testing technology but are also instrumental in examining travellers' sensitivity to its characteristics, such as the absence of a driver and service interface and flexibility.

2.2. Taxonomy of automated demand-responsive transport service

Several public transport systems designed for being operated with AVs have been described in the literature in recent years (Brownell and Kornhauser, 2014; Burns et al., 2013; Fagnant et al., 2015; Fagnant and Kockelman, 2014; International Transport Forum, 2015; Spieser et al., 2014; Zhang et al., 2015). The ADRTS described in these studies can be classified using the following four service dimensions (Winter et al., 2016):

- *Accessibility:* ADRTS can provide stop-to-stop services or door-to-door services.
- *Directness:* a distinction can be made between direct services (no transfers and no intermediate stops) and network services (several fully or partly predefined routes with multiple stops and transfer locations).
- *Vehicle sharing:* vehicles can be shared in space when multiple people ride the same vehicle or in time where a vehicle can be used by different individuals sequentially.
- *Demand responsiveness:* different degrees of demand responsiveness and restrictions on passenger waiting times can be specified.

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