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Optimal infrastructure capacity of automated on-demand rail-bound transit systems

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ABSTRACT

Fully-automated services potentially allow for greater flexibility in operations and lower marginal operational costs. The objective of this study is to determine the capacity requirements of an envisaged automated on-demand rail-bound transit system which offers a direct non-stop service. An optimization model is formulated for determining the optimal track and station platform capacities for an on-demand rail transit system so that passenger, infrastructure and operational costs are minimized. The macroscopic model allows for studying the underlying relations between technological, operational and demand parameters, optimal capacity settings and the obtained cost components. The model is applied to a series of numerical experiments followed by its application to part of the Dutch railway network. The performance is benchmarked against the existing service, suggesting that in-vehicle times can be reduced by 10% in the case study network while the optimal link and station capacity allocation is comparable to those currently available in the case study network. While network geometry and demand distribution are always the underlying determinants of both service frequencies and in-vehicle times, line configuration is only a determinant in the conventional system, whereas the automated on-demand rail service better caters for the prevailing demand relations, resulting in greater variations in service provision. A series of sensitivity analyses are performed to test the consequences of a range of network structures, technological capabilities, operational settings, cost functions and demand scenarios for future automated on-demand rail-bound systems.

1. Introduction

The rapid advancements in the development of fully-automated vehicles have led to an increasing interest in the concept of automated on-demand transit systems. Automated services can potentially allow for greater flexibility in operations and lower marginal operational costs. The area of application considered hitherto has almost exclusively been limited to road-bound systems. To the best of the authors' knowledge, offering flexible services using heavy rail systems as a substitute to scheduled line-based services has not been considered in literature or practice insofar. This paper presents a first step into the relatively unknown area of automated on-demand rail-bound (ADR) systems.

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In this work, an ADR service designed as a full replacement of scheduled heavy rail for a given (sub-)network is envisaged. The automated rail-bound vehicles offer a direct non-stop service and move in the rail network in response to passenger requests with no pre-defined routes and schedules. Vehicles transport passengers that share the same origin and destination stations. Vehicles can be sized according to the operator's preference, but they are considerably smaller than existing train rolling stock units.

The objective of this study is to determine the capacity requirements of ADR systems. Unlike road-bound demand responsive transit services that operate in rural areas or cater for special user groups, the ADR network is designed to serve a large geographical area with relatively high demand that can result in operations being constrained by congestion and capacity limitations. The strategic planning objective of this study constitutes a major difference from most earlier models such as Anderson (1998) and Winter et al. (2016) which considered microscopic, operational models of flexible transport services with a stochastic passenger arrival. The on-demand routing and scheduling features of the envisaged service also sets it apart from studies for planning transit lines with specific network design features, often in urban settings (e.g. Saidi et al., 2016; Fielbaum et al., 2016), and methods for designing timetables that better cater for dynamic demand patterns (Sun et al., 2014).

The development of technological and service concepts that will facilitate ADR systems are still at their early stages. It is therefore not surprising that literature on this service concept is sparse. Automation is a prerequisite for developing such a service given the high costs associated with operating a large fleet of small rail-bound vehicles. An early research identified the challenges of short vehicle headways and limited station capacity in the context of dense urban operations (Bendix and Hesse, 1972). The vehicle engineering RailCab project developed technical and mechanical solutions for small driverless rail-bound traffic (Henke et al., 2008). Vehicle design solutions for operating at short headways in an automated guideway transit system were studied by Choromanski and Kowara (2011), while capacity in relation to station layout has been analysed in more detail by Greenwood et al. (2011). According to UITP (2016), there is more than 800 km operated by automated metro and this is expected to quadruple by 2025 based on confirmed projects. Wang et al. (2016) provide a recent overview of trends and issues related to automated metro operations, including increased capacity and reliability. These studies provide preliminary insights into anticipated advanced in-vehicle technologies and their implications. However, there is lack of knowledge on the capacity requirements that such operations inflict on railway network infrastructure and related system performance and level-of-service. Crucially, none of the previous studies have examined the system requirements of network-wide operations of a flexible rail-bound service.

The contributions of this study are: (i) presenting the concept of an automated on-demand rail-bound transit system and its features; (ii) formulating a novel optimization model for determining the optimal track and station platform capacities for such a system so that passenger, infrastructure and operational costs are minimized. The model is formulated as a cost minimization problem with the premise that system-optimum vehicle flow distribution conditions can be attained; (iii) the underlying relations between technological, operational and demand parameters, optimal capacity settings and the obtained cost components are studied through a series of numerical experiments; (iv) the model is applied to part of the Dutch railway network. The performance is benchmarked against the existing service, its sensitivity to various scenarios is assessed and the implications of which are discussed.

The modeling approach along with the formulation of ADR cost functions and the overall cost minimization problem are presented in the following Section 2. Thereafter, details on model implementation and the specification of model parameters are given in Section 3. A series of numerical experiments designed to test ADR performance under a range of network, demand, costs and technological scenarios are performed in Section 4, followed by an application for part of the Dutch railway network reported in Section 5. We conclude with a discussion of model implications and potential extensions in Section 6.

2. Model formulation

2.1. Modeling approach

Current railway models with lines and timetables as their cornerstone are unsuitable for ADR applications. Passenger transport in general, and the railway planning process in particular, includes successive models for line pool generation, scheduling optimization and methods for infrastructure allocation based on traffic models (Bussieck et al., 1997; Cordeau et al., 1998; Guihaire and Hao, 2008). The main challenge in modelling network-wide long-term planning for ADR is that the model needs to capture flow distribution and capacity constraints without representing system dynamics in microscopic details. Other ADR challenges include the need to handle large numbers of hourly passenger requests, strict routing due to rail infrastructure constraints and highly heterogeneous service characteristics compared to traditional rail systems. The approach taken in this study is to develop a novel macroscopic model by considering ADR as a special case of the network flow problem. This approach allows evaluating a large number of network-wide solutions.

The deterministic and static optimization problem is solved for a given network topology and passenger demand distribution, both are thus exogenous to the model. Other input to the model includes vehicle size, cost units and track and node flow-speed- and delay functions. Model output is the optimal infrastructure capacity per network element – each rail segment and station, vehicle flow distribution and the value of passenger, infrastructure and operational costs.