How to achieve travel time reliability in a transportation network? Evaluating network structure, service frequency and dispatching strategy

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Travel time reliability - for passengers and goods - describes the probability, that passengers or goods arrive at the destination latest at a planned time. Hence, reliability is a fundamental precondition to plan efficient transportation processes, avoiding late arrivals on the one hand, but also limiting the necessity to integrate buffer times on the other hand. We develop a mathematical model to capture the most relevant aspects of network design, which affect the reliability of the network. These aspects are the network structure, the transportation frequency, the dispatching strategy and the probability distribution of the transportation times on the legs of the network. We compute the resulting distributions of the travel time and evaluate the reliability of the network from a user's perspective. Additionally, we also derive some generalized insights. Our model is applicable to many planning tasks, where transportation with transfer and regular services are involved, as end-to-end freight transportation networks (like parcel services, groupage, container transport, airfreight), and multi- and intramodal passenger transport using public transportation (rail, air, bus...).

Key words: transportation networks; service quality; service reliability; distribution of travel times; stochastic model

1. Introduction

Efficient and reliable transportation networks for passengers and goods are an essential part of prospering economies. Networks allow the consolidation of transportation requirements, thus reducing costs and simultaneously helping to reduce the negative impacts on the environment.

Reliability of travel times is an integral part of transportation network service quality. That is, in an optimal solution, passengers and goods need to reach their destination on-time. In the case of passenger air transportation, for instance, flight delays are one of the most established measurements for the quality of service of air transportation (Prince and Simon 2015). Average delays may indicate the service quality, but the distribution of delays, or travel time, is even more critical for the network's reliability (see for instance Knight (1974) and Rietveld (2005)). The distribution of travel times indicates how precisely the travel time for a single trip in the network can be forecast. A precise expectation of the time spent traveling reduces planning uncertainty for subsequent activities. In contrast, high uncertainty entails inefficient buffers in passenger travel or supply chain plans.

Gaver Jr (1968) for instance has formalized and solved the headstart problem (how much earlier to start traveling than required by the expected travel time) using travel time distributions (in this case travel times by car including congestions) and cost functions for early and late arrival.

However, we observe that typical planning approaches consider a minimization of total travel time or total passenger waiting time, which is equivalent to minimizing the average time. van Oort (2014) identified via an extensive survey of public authorities, that reliability of service is of minor relevance in practice, in cases even neglected, at the stage of network design and timetabling.

We study how three aspects of network-based transportation impact the travel time distribution for the entire trip, namely the dispatching strategy (wait or no-wait), the frequency of recurring trips, as well as the structure of the transportation network.

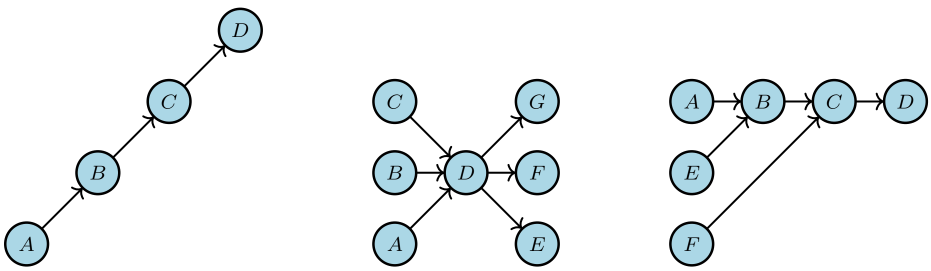
The decision when to dispatch vehicles is a fundamental one in operating transportation networks. In our analysis, we investigate the role of two fundamental control policies for managing the flow of vehicles in the transportation network: waiting for a delayed vehicle (wait) vs. departing on schedule (no-wait). Ginkel and Schöbel (2007) explain the contrasting objectives of both control policies. In the case of ’wait’, no passenger misses her connection, but at the downside that all passengers will arrive late at their destinations. In the case of ’no-wait’ all delayed passengers will miss their connections and will have to wait for the next vehicle which establishes a delay for these passengers. However, other passengers arrive on-time at their destinations.

The frequency of trips tightly relates to the dispatching strategy since it will be inefficient to wait for connecting passengers beyond the arrival of the next vehicle to travel along the same line, given there are not capacity constraints. Thus, the trip frequency acts as an upper limit to the waiting time distribution in the network. Rietveld (2005) qualitatively discusses departure frequencies in multimodal chains. For the case of egress from a main station, he argues that low frequencies on the last mile transport worsen increase uncertainty in the total travel time as missing a connection is rather costly in case schedules are not coordinated.

The network structure further impacts the distribution of travel times as, for instance, transfers become more challenging as more vehicles connect to a subsequent vehicle.

2. Modeling Description

We analyze different cases of networks, see Fig. 1. We assume that the vehicles are not a limited resource. We refer to total travel time of a trip in a transportation network as the sum of all individual leg travel times plus intermediate waiting times at transfer stations.



(a) Linear network (b) Hub-and-spoke network (c) Fishbone network

Figure 1. Network structures under consideration

3. Solution Approach

A distinction can be made between the means of transport view and the passenger view. The travel time of the means of transport from a start node to an end node as well as the distribution of the arrival delay per station can be calculated iteratively by cutting off distributions in combination with convolution. Depending on whether the ”no-wait” or ”wait” control policy is applied, additional steps must be performed. For the control policy ”wait”, a maximum function of the travel time distributions is determined from the individual distributions of the means of transport. After calculating the travel time distribution of the means of transport from a start node to an end node as well as the distribution of the delay of arrival per station, the travel time distribution of a passenger can be determined. It is assumed that a passenger changes the means of transport at most once.

4. Numerical Evaluation

We conduct experiments along four essential dimensions, in order to gain insights on the system's behavior as the context changes. The analysis investigates the three common network structures illustrated in Fig. 1. For each of these structures, we run multiple experiments to highlight the effects as the networks become more complex. Demand plays an important role in the model and we model two options. One is uniformly distributed demand between all nodes the network. In contrast, we compare to the case where there is one stream of dominating demand in the model. We compare two delay distributions, a low variance and a high variance case. We compare a policy of 'wait' vs. a policy of 'no-wait' for all cases.

The results show that different network structures have a specific profile in terms of network size and operating frequencies on the threshold for wait / no-wait policy. The expected travel time of no-wait policy is superior to that of wait policy as networks grow. However, the 99% quantile of the travel time with the no-wait policy is significantly higher than the travel time with the wait policy, regardless of the network size and structure. In case the timetable is repeated more frequently, the no-wait policy is attractive even for small networks.

5. Conclusions

Our work contributes strategic insights for reliable vehicle scheduling. We analyze the distribution of travel times as a combination of control policies and network structures. Further research can be conducted on generalising the model and extending the model with additional control policies.

References

Gaver Jr, D. P. 1968. Headstart strategies for combating congestion. *Transportation Science* **2**(2) 172–181.

Ginkel, A., A. Schöbel. 2007. To wait or not to wait? the bicriteria delay management problem in public transportation. *Transportation Science* **41**(4) 527–538. doi:10.1287/trsc.1070.0212.

Knight, T. E. 1974. An approach to the evaluation of changes in travel unreliability: a “safety margin” hypothesis. *Transportation* **3**(4) 393–408.

Prince, J. T., D. H. Simon. 2015. Do incumbents improve service quality in response to entry? evidence from airlines' on-time performance. *Management Science* **61**(2) 372–390.

Rietveld, P. 2005. Six reasons why supply-oriented indicators systematically overestimate service quality in public transport. *Transport Reviews* **25**(3) 319–328.

van Oort, N. 2014. Incorporating service reliability in public transport design and performance requirements: International survey results and recommendations. *Research in Transportation Economics* **48** 92–100.