Let's Build a Tunnel! – A Closer Look at Cologne's New Subway Routes

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Abstract. Once planning and construction will be complete, Cologne's new subway tunnel will enable fast and direct transportation between the central and southern urban quarters, and the city's central station. This paper takes a closer look at the project's four decades spanning history, its characteristics, and the impact of its integration on the overall system's performance.
When representations of the tunnel and the re-routed light-rail lines are integrated with an existing simulation model, experiments show that no negative impact on the network's performance is to be expected. Some weaknesses are discovered, resulting for example in delayed departures at the tunnel's stations.

Introduction

In the year 1992 the City of Cologne, Germany, decided to build a new subway route under its city center. Construction of the 6.6 kilometer route was planned to be executed in three phases (see Figure 1): during the first phase a new subway tunnel would be built under the city center, creating a fast and direct connection of the central and southern urban quarters to Cologne's central station; during a second phase this tunnel would be extended to connect to existing tracks north of station Schönhauser Strasse at the river Rhine; and as a third phase the tracks leaving the southern end of the tunnel would be continued further south with five new stations and a Park and Ride station being added. When construction began in 2004 the complete system was planned to be operational in 2011.

Almost from the beginning the construction process was ridden with incidents: In September 2004 residents living next to the construction site woke up one morning to find that the tower of the neighborhood church St. Johann Baptist was visibly tilted (see [2]). In November 2004 significant construction-related damage was detected in arches and ceiling of the St. Maria im Kapitol church (see [11]). In August 2007 the tower of the Historic City Hall was found to have shifted (see [21]). Also in summer 2007 a natural gas pipeline was damaged in the course of the constructions, resulting in evacuations and enforced electricity cut-offs in major parts of the city center (see [18]).

Finally, on March 3, 2009 a foundational wall in the 25 meter deep excavation at Waidmarkt square broke, causing the Cologne Historical Archive building and two neighboring residential buildings to collapse into the construction pit, killing two residents and burying 30 shelf kilometers of historical records documenting 1,200 years of local and regional history (see [2]).

When it became known that only 20 percent of the mandated steel joists had been used in the construction of the foundational wall, and that instead of the permitted three a total of 15 well pumps had been installed to keep a much higher than expected volume of water from flowing back into the pit, the state secretary of transportation called the affair "obviously criminal," requesting swift and thorough investigations (see [4]). Eight years later, at the time of this writing, still no-one was indicted in connection with the incident (see [10]).

In the aftermath of the disaster 519 buildings along the construction site were checked, with approximately 300 of them showing significant damage caused by the tunnel's construction (see [19]). Later, when the first vehicles traversing the tunnel caused vibrations in Cologne Cathedral's foundations, a low maximum speed was prescribed for the tunnel segments adjacent to the historic landmark. This issue was allegedly solved by the installation of rubber dampers (see [3]).

At the time of this writing parts of the new subway routes have commenced operation, with the central part around the still open Waidmarkt excavations and the southern extensions still missing. The City now plans the completion of construction and the start of full operations for 2023 (see [13]).

This paper takes a closer look at Cologne's new subway tunnel – its characteristics, its integration with the light-rail network, and potential bottlenecks. To examine the tunnel's expected impact on the network's overall performance a simulation model for timetable-based tram traffic first proposed in [15] is applied.

The paper continues with an overview of the applied simulation model, the tunnel's characteristics and its integration with the model (see Section 1), and then discusses a set of experiments designed to examine the impact the tunnel's integration might have on system performance (see Section 2). The paper concludes with a short summary of the lessons learned (see Section 3).

1 Modeling Cologne's central subway tunnel

1.1 Simulation model

Cologne's light-railway system is mixed – trams travel on underground tracks as well as on street level, and are thus subject to individual traffic and corresponding traffic regulation strategies. Most rail-bound traffic simulations are designed for long distance train or railway networks (see e.g. [17], [20]). While those systems feature similarities to tram networks (see [7], [9], and [22]), e.g. passenger exchange or maneuvering capabilities, they differ greatly in other aspects, e.g. the continuous use of safety blocks.

Subsequently, the applied model (described in detail in [15]) represents tram behavior as a mixture between train and car behavior, e.g. line-of-sight operating and driving. The mixed tram network is modeled as a directed graph with platforms, tracks and track switches represented by nodes. Neighborhood relations between these elements are represented as edges. Figure 3 shows part of the examined network, which is mapped on the graph depicted in Figure 4, where rectangles represent platforms, lines represent tracks and triangles track switches. Stations are defined as sets of geographically related platforms that are connected by walkable infrastructure.

Figure 1: Planned route of Cologne's new subway tunnel, stations, interconnections, and line routes.

The operational logic of transit vehicles is encapsulated in agents (see [16]), with the simulation engine's mechanics being based upon the event-oriented approach (see [1] or [25]). Thus agents change their state while executing simulation events of certain types at discrete points in simulation time. These state changes may trigger a change in the overall system state and generate follow-up events that are fed to appropriate agents. Main tram characteristics are specified by the type of tram, which holds functions for the maneuvering capabilities, e.g. acceleration and braking. The simulation's main stochastic parameters are the probability p_d of introducing small delays in any acceleration activity, and the triangular distribution parameters $a_{h,v}$, $b_{h,v}$, and $c_{h,v}$ for the duration of passenger exchange (see Figure 2), which are specific to platform h and tram type v. Here, the combined duration of opening and closing the vehicle doors m_v serves as a minimum value (see [14]).

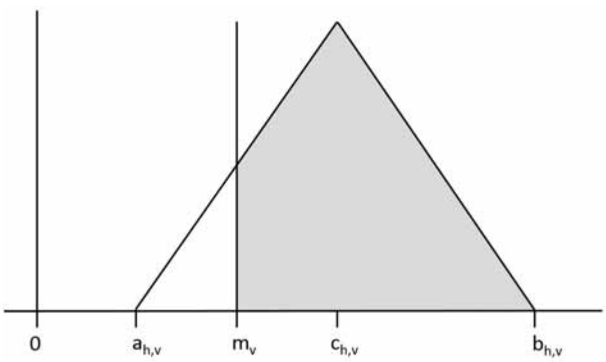

Figure 2: Density of passenger loading time distribution with minimum m_v and triangular distribution determined by parameters $a_{h,v}$, $b_{h,v}$, and $c_{h,v}$.

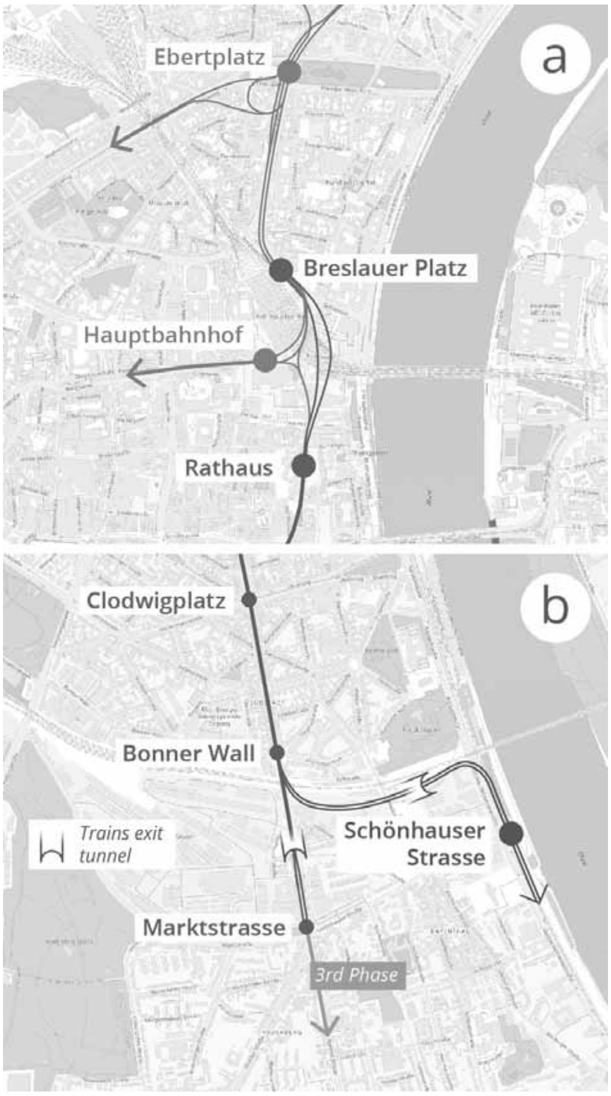

Figure 3: Planned integration with the existing light-rail network in the north (a) and south (b).

1.2 Cologne's central subway tunnel

The tunnel itself (for the construction-related information presented in this sub-section see [12]) is approximately 4 kilometers long and positioned between 11.5 and 28.5 meters underground. It is lined by eight new or significantly extended stations (see Figure 1): Breslauer Platz, Rathaus, Heumarkt, Severinsstrasse, Karthäuserhof, Chlodwigplatz, Bonner Wall, and Marktstrasse. The low average distance between two stations of approximately 570 meters is justified by the high housing density in Cologne's city center.

At its northern end the tunnel is connected to the existing network at the extended station Breslauer Platz, positioned between stations Ebertplatz, Hauptbahnhof, and Rathaus (see Figure 3 (a)). A cluster of switches lies between Ebertplatz und Breslauer Platz – these have to be navigated in configurations dependent on a vehicle's route. Another set of switches lies between Breslauer Platz, Hauptbahnhof, and Rathaus. As switches typically only allow low maximum traversal speed, and are additionally shared between vehicles of different lines, they potentially turn out to be bottlenecks in transit systems (see [26]).

At its southern end the tunnel splits between stations Bonner Wall and Marktstrasse, with one branch continuing south servicing a yet to be built chain of stations towards station Arnoldshöhe, and the other branch leading east where it integrates to the existing network via another set of switches north of the existing station Schönhauser Strasse at the river Rhine's bank (see Figure 3 (b)). Here, another potential bottleneck arises with the new tracks crossing the major artery Gustav-Heinemann-Ufer at ground level, necessitating either wating times for the transit vehicles, or a transit signal priority system with frequent waiting periods for individual traffic on the highway – an option that might be politically hard to justify. The alternative option of an extended tunnel to the east side of Gustav-Heinemann-Ufer, which would have eliminated the ground level crossing, was not realized – primarily for budget reasons.

To service the added stations some line routes are changed: Line 5 leaves its current route to enter the tunnel at station Hauptbahnhof, traverses it, services stop Bonner Strasse, and then goes on to station Arnoldshöhe in the south. Line 16 leaves its old route north of station Schönhauser Strasse, and services the stations Bonner Wall, Chlodwigplatz, Kartäuserwall, Severinsstrasse, Heumarkt, and Rathaus before exiting the tunnel at Breslauer Platz. This rerouting relieves the existing east-west tunnel under the town center around Neumarkt station, which line 16 traverses under the current schedule. Line 16 is complemented by a trunk line 16A servicing the stops between Ebertplatz in the north and Marktstrasse at the tunnel's south end, enabling a higher service frequency in these densely populated areas. These three routes are planned to operate in ten minute intervals each, resulting in tunnel stops being serviced every three to four minutes.

To represent these features each platform, split, and track segment is integrated as a node in the existing model graph (see Figure 4). Platforms are attributed with parameters for the passenger exchange time distribution, splits are attributed with a typically low local maximum velocity, while track segments are attributed with length, planned traversal times, and maximum velocities that might parametrize local conditions like tight bends, slopes, or pedestrian zones.

Cologne's light-rail network is serviced by vehicles of types *Flexity Swift K4000* (see [27]), *K4500* (see [28]), and *K5000* (see [29]) by Bombardier Transportation. The agents representing these vehicle types are attributed with basic maneuvering attributes, e.g. acceleration and deceleration functions, as well as typical

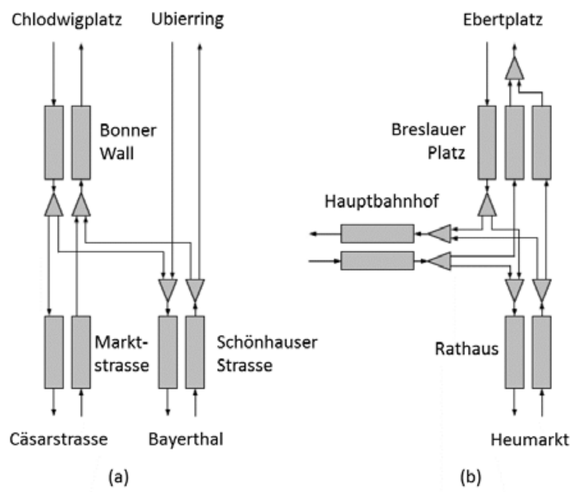

Figure 4: Model representations of the tunnel at its (a) southern and (b) northern end points .

and maximum velocity, passenger capacity, and parameters for the passenger exchange distribution.

2 Experiments

2.1 Scenario and parameters

As the exact timetable to be applied to the reformed routes 5 and 16 has not yet been announced, a discrete optimization model (described in detail in [24], for recent overviews of timetable optimization models see [5] and [6]) combining a genetic algorithm (see [8]) and a branch-and-bound solver is used to generate timetables optimally fitted to the network's characteristics. While the optimization process starts out with an initial population M_i of timetables that are typically not well adapted to the network, timetables from the set of optimum timetables M_o show maximal regularity and best possible adherence to basic transport planning requirements at the same time. Contrasting simulation results for these two sets of timetables allows to examine the impact of regular timetabling on Cologne's new light-rail tunnel, and by extension the impact of the tunnel on overall network behavior.

The optimization model uses regularity of scheduled time offsets between two consecutively departing vehicles at a platform as an indicator for a timetable's robustness against disturbances resulting from small, inevitable delays. For example, in an assumed interval of ten minutes two lines could be scheduled with equidistant offsets of five minutes, which means that vehicles of one or both involved lines could be late for more than four minutes without consequences for vehicles of the following line. Under an extremely unequal split of the available time span into a nine minute offset followed by a one minute offset, vehicles of the first line could have a delay of more than eight minutes without consequences to vehicles of the following line. On the other hand, would the vehicle of the second line be even slightly late, the delay would spread to the follow-up tram. Since we assume typically small operational delays, we see a regular offset distribution as very robust, the occurrence of very small offsets as not robust (see [26]).

Starting out from an objective function value of 191.19 the optimizer yields a plateau of 282,000 optimum solutions with a objective function value of 174.64, an improvement of nominally 8.7 percent. For a first set of experiments ten timetables each are selected randomly from the pool of initial candidates M_i and from the pool of optimum solutions M_o. For each of these timetables ten runs simulating typical operational days are executed. For a more specific look on areas where calculating averages between different timetables does not yield real insight two timetables $\mu_i \in M_i$ and $\mu_o \in M_o$ are selected. For each of these two timetables 100 simulation runs are executed.

For each of these simulation runs a moderate probability of operational delays $p_d = 0.3$, and a moderate distribution of passenger loading times with $a_{h,v} = 0$, $b_{h,v} = 30$, $c_{h,v} = 15$, and a minimum of $m_v = 12$ is assumed (for a detailed discussion of these parameters see [14]).

2.2 Results and discussion

Averaging over all stops in the network and all timetables in M_i, the simulation runs yield an average delay of departures of 20.0 seconds, with a reduction of 3.2 seconds or 16.0 percent to 16.8 seconds under the timetables in M_o. This behavior is consistent with observations made of the Cologne network in its state before the tunnel's completion, which depict a reduction from 19.4 by 3.4 seconds or 14.4 percent to 16.0 seconds (see [23], pp. 156-174). Disregarding punctual departures the average delay is reduced from 36.6 down to 31.4 seconds, a reduction of 5.2 seconds or 14.3 percent. This again is comparable with a reduction from 36.8 by 5.3 seconds or 14.4 percent to 31.5 in the pre-tunnel network.

As described, as part of the planned service line 16 will be rerouted through the new north-south tunnel. The stations in the existing east-west tunnel – which it currently traverses – will be served by one line less, allowing for larger intervals between individual vehicles. Accordingly, departures in the existing tunnel show an average delay of 3.3 seconds for the planned service, independent of the examined schedule. This is a slight reduction in comparison to average pre-tunnel delays of 6.5 seconds under initial timetables, and 4.4 seconds under optimum timetables.

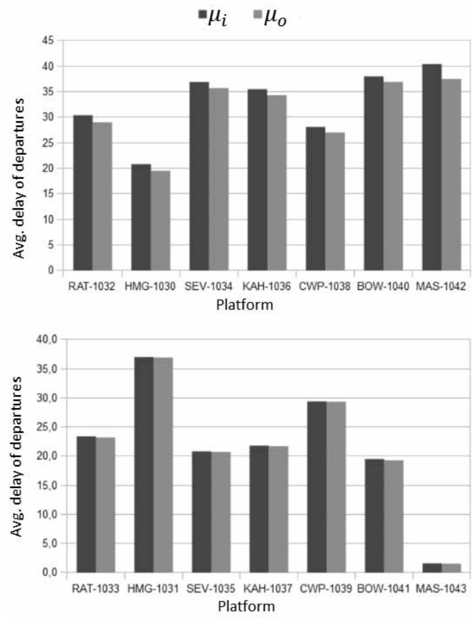

Figure 5: Average delays of departures at stations in or near the light-rail tunnel: southbound (top) and northbound (bottom).

More interesting than these general indicators is a closer view of the light-rail stations in the tunnel and at its entries and exits: Averaged over all tunnel platforms the departure delay is reduced slightly from 21.2 seconds under timetable μ_i to 19.5 seconds under μ_o, a decrease of 8.0 percent or 1.7 seconds. While the departures at platforms oriented southbound show a slight delay reduction, the northbound platforms show no significant change (see Figure 5). With the average delay barely changing under different timetables, the relatively high (with exception of the northbound tunnel entry point Marktstrasse, MAS-1043) basic delay values from 19.3 to 37.5 seconds have to be dependent on other factors. To examine this situation closer, the tunnel-traversing line routes 5 and 16 are discussed.

The delay development of southbound routes 5 and 16 (see Figure 6 (a) and (b)) share central characteristics: Both routes show increases in delay of approximately 16 to 18 seconds between Heumarkt (HMG) and Severinsstrasse (SEV), and of approximately 20 seconds between Chlowigplatz (CHW) and Marktstrasse (MAS). In addition, line 16 has a relatively high delay plateau of approximately 53 seconds when entering the tunnel, which can be explained by the necessity to navigate the highly loaded switch clusters between Reichensperger Platz (RPP), Ebertplatz (EBP), and Breslauer Platz (BRE). It regains some punctuality (approximately 24 seconds) between stations Breslauer Platz and Heumarkt.

For the northbound routes 5 and 16 (see Figure 6 (c) and (d)) the simulation shows delay increases of approximately 16 seconds between Severinsstrasse and Heumarkt, as well as gained punctuality of approximately 29 seconds between Heumarkt and Hauptbahnhof (DOM), and 36 seconds from Heumarkt to Breslauer Platz, respectively. Route 16 shows a relatively high delay of approximately 32 seconds when entering the tunnel at Schönhauser Strasse (SHS).

The simulation demonstrates that the transit vehicles leave the tunnel with approximately the same delay they have when entering it, without displaying significant differences in amount and development of delays under different timetables. The delays are therefore not dependent on the applied schedule, but on other bottlenecks: the switch clusters with their low maximum velocity, and the trains' acceleration and deceleration capabilities that are not adequate to counterbalance delays developing on the relatively short track segments.

Increasing the scheduled traversal time between Reichensperger Platz and Ebertplatz for southbound trains, and before Schönhauser Strasse for northbound vehicles would eliminate most delays. This could be at least partially compensated by reducing the planned traversal time between Heumarkt and Breslauer Platz. Alternatively, using vehicles with higher typical acceleration and deceleration capacities would yield a higher average velocity on the short track segments between tunnel stations.

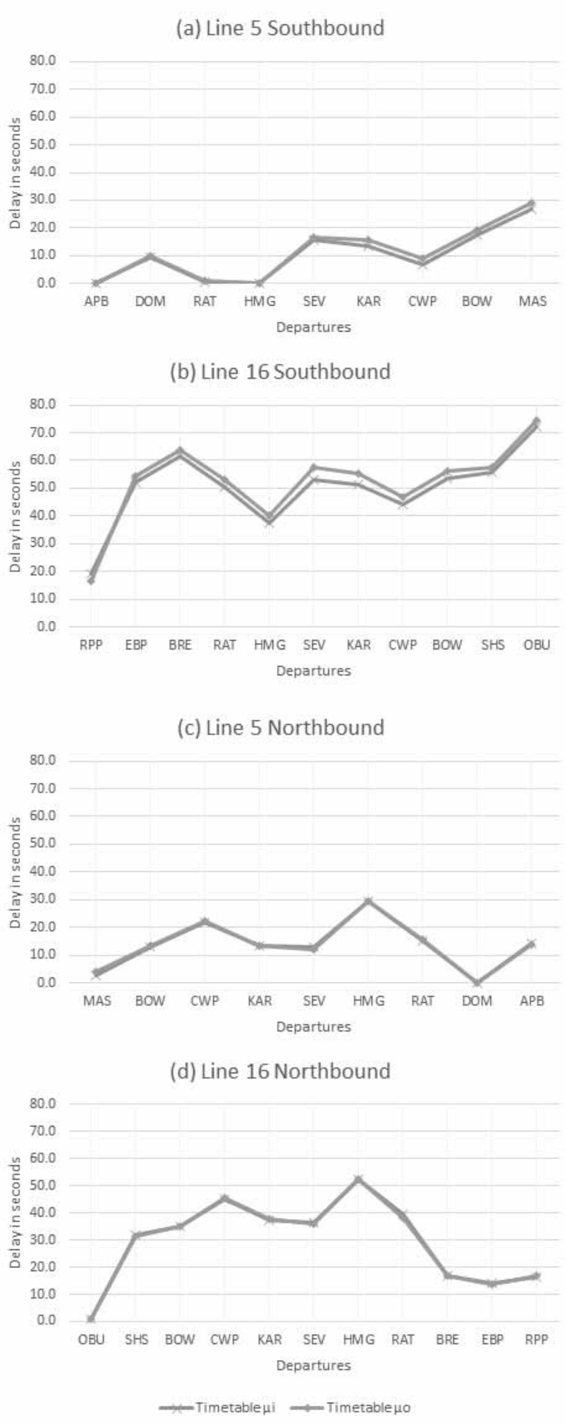

Figure 6: Average delays at departures for line routes 5 and 16 in or near the subway tunnel: southbound ((a) and (b)) and northbound ((c) and (d)).

3 Conclusions

This paper examined the planned subway tunnel connecting Cologne's central station with the central and southern urban districts. After describing characteristics of the tunnel, and the integration of the tunnel and the re-routed subway lines with a simulation model of Cologne's light-rail transit network, some experiments were conducted to both estimate the tunnel's impact on system performance, and the to be expected delays originating from small operational disturbances.

The experiments showed that no overall negative impact on the transit system's performance would have to be expected from the tunnel's integration. While the simulation predicts significant delays at platforms in and around the tunnel, these could be mitigated by increasing the planned traversal time by one minute, in particular in the vicinity of the southbound platform Ebertplatz and the northbound platform Schönhauser Strasse. Deploying transit vehicles with improved acceleration and deceleration capabilities also would increase the tram's average velocity and reduce the observed delays.

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