# Modelling the Prohibition of Train Crossings in Tunnels with Blocking Time Theory 

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#### Abstract

Preventing both passenger and freight trains from crossing each other in double-track railway tunnels is a fire safety measure required by the German railway authority in order to prevent fatal accidents. The prohibition poses a restriction on infrastructure usage that has to be incorporated in rail traffic planning. While it has already been implemented in timetabling and simulation tools, its effects on line capacity in long-term strategic planning has not been investigated so far. This paper presents a method to incorporate restrictions on simultaneous track usage in the blocking time calculation and minimum headway time estimation. The effects on line capacity are analysed quantitatively based on the STRELE approach, which is an analytical method for strategic long-term capacity planning currently used by German railway infrastructure manager DB Netz AG. Results are validated by comparison to delay increase in microscopic simulation of train operations.


## Keywords

Analytical methods, Capacity, Safety, Train crossings, Tunnels

## 1 Introduction

Tunnels are critical elements for safe operation of rail traffic. Even though accidents occur less often inside railway tunnels, the damage caused by fire in such a closed environment with limited accessibility can be catastrophic. Especially trains carrying dangerous goods pose a fire hazard and should not be scheduled to cross oncoming passenger trains in order to avoid fatal fires (UIC (2003)). For German infrastructure, the federal railway authority Eisenbahn-Bundesamt (2008) prohibits all freight trains from crossing passenger trains in new tunnels that are longer than 500 meters.

Timetabling and simulation tools used for the German market such as RUT-K (Brünger and Gröger (2003)), LUKS ${ }^{\circledR}$ (Janecek and Weymann (2010)) or RailSys ${ }^{\circledR}$ (Radtke and Bendfeldt (2001)) need to incorporate the prohibition of passenger and freight trains from crossing each other in tunnels. In simulations with the software LUKS ${ }^{\circledR}$ both directions of a double-track railway line are evaluated simultaneously and restrictions on simultaneous track usage in tunnels is already implemented. Whenever a prioritized passenger train passes through the tunnel, it occupies the other direction for freight trains. Freight trains need to wait in front of the entry signal for the passenger train to leave the tunnel.

The effects on line capacity in long-term strategic planning have not been investigated so far. UIC (2004) defines capacity as the number of trains in a fixed time period, which can be operated with market-orientated quality. Evaluating the existing and future capacity is necessary for the recognition of bottlenecks. It is essential to make optimal use of the rail network and to expand the infrastructure where necessary in order to meet the constantly
increasing demand for transportation.
This paper presents a method to include restrictions on simultaneous track usage in the blocking time calculation. Mean obstructions caused by the prohibition of train crossings in tunnels are characterized by extended blocking times. Blocking times are required to calculate minimum headway times, which are important input parameters for long-term capacity planning. To assess the effects quantitatively, the modelling is included in the blocking time based STRELE formula by Schwanhäußer (1974). This method is a strategic planning framework based on stochastic prognosis of knock-on delays and is the standard method for capacity planning of railway lines used by German infrastructure manager DB Netz AG (DB Netz AG (2009)).

The following chapter 2 gives a detailed overview of existing methods to evaluate capacity. Chapter 3 presents the new method to modify blocking times. This method is applied for capacity analysis with the STRELE approach in chapter 4 with results being validated by comparison to delay increase in microscopic simulation of train operations.

## 2 Capacity Assessment

This chapter gives an overview about different methods for capacity assessment such as simulations or analytical approaches. Essential for these methods is a basic knowledge about the blocking time theory, which is provided in advance.

### 2.1 Fundamentals

The infrastructure occupancy can be described based on blocking times (Happel (1959), UIC (2013)). The train's operational occupancy of a section takes longer than the purely physical occupancy. Before the train runs through a section, it is already blocked for the route setup time $t_{\text {setup }}$, the signal watching time $t_{\text {sight }}$ and the approach time $t_{\text {approach }}$. After the actual running time $t_{\text {running }}$, the clearing time $t_{\text {clearing }}$ and the release time $t_{\text {release }}$ block the section before the next train movement can occupy it (Pachl (2014)). The sum of these time elements represents the entire blocking time, which is illustrated in Figure 1. Blocking time theory can even be applied for different train control and signalling systems, such as ETCS (Wendler (2009)).


Figure 1: Blocking time and its elements

The graphic sequence of blocking times forms a blocking time stairway. Blocking time stairways of two trains demonstrate the minimum temporal distance in which they can follow each other free of obstruction. This duration is called minimum headway time and is measured for each overtaking section. The minimum headway time starts at the beginning of the blocking time of the preceding train and ends at the beginning of the blocking time of the subsequent train (see Figure 2). Minimum headway times refer to the common itinerary on an overtaking section of two trains. The overtaking section with the largest minimum headway time is decisive for the entire track (Nießen (2014)).


Figure 2: Minimum headway time $\mathrm{t}_{\mathrm{h}, \mathrm{ij}}$

In scheduled timetables, running time supplements and buffer times are added to absorb smaller train delays. A train delay is a deviation from the timetable. According to the location and cause of generation, delays can be classified: Primary delays are not caused by other trains but are due to disruptions such as technical failures, large passenger volumes or bad weather conditions. Following these primary delays, a delayed train might hinder other trains and cause so-called knock-on delays (Yuan and Hansen (2007)).

### 2.2 Simulations

A simulation imitates the real operation process in a way that a given timetable is perturbed randomly by primary delays in many different runs and models the resulting propagation of train delays in the railway network. It is possible to include special characteristics of the infrastructure or the operating program. Thus, simulations are especially suitable for complex track layouts and timetables, which are known in detail. Modelling the infrastructure and timetable with the simulation tool requires extensive work. The results, such as delay developments and punctuality, are only valid for the examined timetable. Calculating general performance indicators is only possible by iteratively simulating a large number of different timetables (Watson and Medeossi (2014)).

Microscopic simulation models are generally divided into synchronous and asynchronous models. In synchronous simulations, all trains are modelled simultaneously. The operation process is reproduced in time steps and in each time step, concurrent occupations are resolved under consideration of priorities. Synchronous models allow a realistic representation of train traffic with all trains interacting between each other (Jacobs (2008), DB Netz AG (2009)).

Asynchronous simulations perform within a strictly descending hierarchical structure:

Trains are modelled ordered by their priority. First, trains with the highest priority are modelled and occurring conflicts are solved with a "first come, first serve" strategy. Resulting infrastructure occupations are fixed and stored. After that, the next priority group of trains is added to the time-distance-diagram and simulated in the same way (Watson and Medeossi (2014)).

### 2.3 Analytical Capacity Assessment

For the management and operation of railway systems, it is extremely important to evaluate the capacity of railway infrastructure. This knowledge constitutes the necessary basis to decide which measure - changing the infrastructure or its usage - is most effective to satisfy a growing traffic demand.

In Europe, the timetable compression method proposed by the International Union of Railways (UIC (2013)) is common to evaluate the capacity of a railway line. This method is based on the blocking time theory. Compressed blocking time stairways use the infrastructure during the occupancy time. The so-called concatenated occupancy rate then results from the ratio of the occupancy time to the investigation period. UIC (2013) recommends values for occupancy time rates for three different types of lines. Adding extra trains until the recommended occupancy time rate is reached leads to the line's capacity.

Capacity consumptions of a timetable consist not only of infrastructure occupation but also of timetable stability. Timetable stability is the ability to absorb delays. Ideally, delayed trains return to their scheduled train path by using the time allowances in the timetable. Goverde (2005) developed an analytical approach to evaluate network dependencies on timetable stability. The max-plus analysis approach is used to model a scheduled railway system and has been implemented in the software tool PETER (Goverde and Odijk (2002)).

Another software tool to assess the quality of timetables is OnTime. It combines the stochastic mapping of delay and the analytical calculation of delay propagation (Büker and Seybold (2012)).

In long-term strategic planning only limited knowledge about the future timetable is available, which requires stochastic tools to evaluate capacity. Schwanhäußer (1974) introduced an approach based on queueing theory for capacity evaluation. Since this approach is used for the case study (chapter 4), it is described in detail below. Wendler (2007) aims to predict the scheduled waiting time by means of a semi-Markovian queueing model. A discussion about queueing based approaches to assess the capacity of railway lines in Germany can be found in Weik et al. (2016).

Several papers focus on the capacity assessment of the railway system as a whole. A queueing network model is provided in Huisman et al. (2002). Mussone and Calvo (2013) present an analytical method based on an optimization model to assess the capacity of a railway system.

## Analytical Method STRELE

In Germany, the timetable-independent analytical method by Schwanhäußer (1974) and Schwanhäußer (1994), which aims to determine the capacity of a railway line by calculation of expected waiting times, is widely used. A line is decomposed into overtaking sections.

Between two overtaking stations, the STRELE formula estimates mean knock-on delays

$$
\begin{align*}
\bar{K}= & \left(p_{\text {del }}-\frac{p_{\text {del }}^{2}}{2}\right) \cdot \frac{\bar{t}_{\text {del }}^{2}}{\bar{b}+\bar{t}_{\text {del }} \cdot\left(1-e^{-\frac{\bar{t}_{h}}{\bar{t}_{\text {del }}}}\right)} \cdot\left[p_{e q} \cdot\left(1-e^{-\frac{\bar{t}_{h, e q}}{\bar{t}_{\text {del }}}}\right)^{2}+\right.  \tag{1}\\
& \left.\left(1-p_{e q}\right) \cdot \frac{\bar{t}_{h, \text { diff }}}{\bar{t}_{\text {del }}} \cdot\left(1-e^{-2 \cdot \frac{\bar{t}_{h \text { diff }}}{\bar{t}_{\text {del }}}}\right)+\frac{\bar{\epsilon}_{h}}{\bar{b}} \cdot\left(1-e^{-\frac{\bar{t}_{h}}{\bar{t}_{\text {del }}}}\right)^{2}\right] .
\end{align*}
$$

| Input parameters for this formula are |  |
| :--- | :--- |
| $p_{\text {del }}$ | mean probability of primary delays, |
| $\bar{t}_{\text {del }}$ | mean time of delay of delayed trains, |
| $\bar{b}$ | mean buffer time, |
| $p_{\text {eq }}$ | probability of two trains with equal rank, |
| $\bar{t}_{h}$ | mean minimum headway time, |
| $\bar{t}_{h, e q}$ | mean minimum headway time between trains with equal rank and <br> $\bar{t}_{h, \text { diff }}$ |
| mean minimum headway time between trains with different rank. |  |

A defined level of service, which regulates the maximum admissible sum of knock-on delays, has been defined based on a statistical analysis of operation data to assess the optimal quality in operation. Calculated knock-on delays are compared with permissible waiting times in order to determine the capacity of the investigated railway line. DB Netz AG (2009) specifies quality levels for Germany. Admissible knock-on delays $\operatorname{adm} \sum K$ on railway lines are defined as

$$
\begin{equation*}
\operatorname{adm} \sum K=t_{I} \cdot q \cdot 0,260 \cdot e^{-1,3 \cdot p t r} \tag{2}
\end{equation*}
$$

Input parameters for this formula are the investigation period $t_{I}$, the quality factor $q$ ( $q=1$ for optimal quality) and the ratio of passenger trains $p_{p t r}$. Equating the STRELE formula to the level of service specified by Eq. (2) and solving for the buffer time, the minimum required buffer time $b_{\text {req }}$ can be calculated. The corresponding number of trains $n$ is obtained by

$$
\begin{equation*}
n=\frac{t_{I}}{\bar{t}_{h}+b_{r e q}} \tag{3}
\end{equation*}
$$

The STRELE formula is implemented in software tools such as LUKS ${ }^{\circledR}$, which is the standard tool for capacity calculation in Germany. Even though the method is mainly used in Germany, it is transferable to any other infrastructure manager or analyst.

This approach is mainly used in long-term planning since it does not require an existing timetable. Merely little knowledge about the timetable e.g. train frequencies is necessary. Thus, it is suitable for comparing different infrastructure designs regardless of the precise operation concept. Compared with simulations, it takes less computing time to determine the capacity of a railway line. The performance indicators are easy to compare with defined limits and possess a validity extending far into the future.

## 3 Method

This chapter shows how the prohibition of train crossings can be included when calculating blocking times and how this transfers to the capacity assessment with the STRELE formula. In many cases, passenger trains have priority over freight trains. For an easier understanding, passenger trains are defined as priority trains in the following text, except otherwise stated. The method is applicable accordingly if the priorities are defined differently.

### 3.1 Restrictions for Tunnel Utilization

For German infrastructure, the federal railway authority defined which tunnels are affected by the prohibition of freight trains crossing passenger trains (Eisenbahn-Bundesamt (2008)). The prohibition applies for new double-track tunnels with a length of more than 500 m . When the tunnel length exceeds 1000 m , separate tubes for each direction are recommended.

In order to prevent passenger and freight trains from crossing each other in a tunnel, freight trains need to stop and wait at the tunnel's entry signal until the passenger train has cleared the infrastructure. As long as passenger trains are prioritized over freight trains, this prohibition supposedly only disturbs freight trains but may cause knock-on delays to more trains.

When two tunnels are built closely together and the distance between them is too short for a freight train to stop, they cannot be occupied separately. These tunnels are modelled as one continuous tunnel.

The following sections describe the method quantifying the effects on freight trains using modified blocking times. In tunnel blocks, blocking times are extended by the mean time a freight train needs to stop and wait for the prioritized passenger train to leave the tunnel. In section 3.2, the occupancy time of passenger trains is determined. Section 3.3 estimates the number of freight trains, which get disturbed and need to wait for passenger trains to leave a tunnel. With this information, it is possible to calculate new blocking times for the affected freight trains in section 3.4. Extended blocking times in relevant blocks lead to longer minimum headway times (section 3.5), which are input parameters of the STRELE formula. Mean knock-on delays increase with longer minimum headway times and reduce the capacity of a line.

### 3.2 Occupancy Time Rate

As long as a passenger train drives through a tunnel, freight trains need to wait at the tunnel's entry signal. During the occupancy time $t_{o, i}$, the passenger train $i$ occupies the tunnel and prevents freight trains from entering. The occupancy time applies for the whole tunnel's length, which in the following example extends into two blocks. In Figure 3, solid lines show the division of block sections in the direction Node A - Node B and broken lines show the division in the opposite direction. The overall occupancy time of the tunnel begins at the tunnel's entry signal and ends at the location of the entry signal for the opposite direction. At this location, there is usually a clearing point to control that a train has left the tunnel. If this is not the case, the occupancy time prolongs up to the next clearing point.


Figure 3: Occupancy time $t_{o, i}$

Occupancy times may overlap when trains of the same category follow each other through the tunnel. This occurs particularly in tunnels divided into several blocks. Two passenger trains with overlapping occupancy times prevent a freight train from entering the tunnel concurrently. In Figure 4, prioritized passenger trains $i$ and $j$ occupy the tunnel at the same time. The time during which both trains prevent a freight train from entering the tunnel is called overlapping time. The overlapping time reduces the total occupancy time of passenger trains and therefore the obstruction of freight trains. With this information, a mean occupancy time $\bar{t}_{o}$ can be calculated, which describes how long passenger trains occupy the tunnel on average.


Figure 4: Overlapping of the occupancy times $t_{o, i}$ and $t_{o, j}$

When two passenger trains follow each other within a short period of time, a freight train with lower priority lets both trains pass in order not to disturb the passenger trains. To respect this priority, an operational service time supplement $t_{S}$, which extends the time frame during which a low priority train gets disturbed, is included. During this additional time, the tunnel is already blocked for the prioritized passenger train even though it has not entered the tunnel yet. Like occupancy times, service time supplements of two prioritized trains can overlap. Overlapping happens mainly in long tunnels. During the overlapping of the service time supplement $\bar{t}_{s, o}$, both passenger trains disturb the freight train. This reduces the total occupancy time of prioritized trains $T_{o, p r i o}$, which includes occupancy times and service time supplements for these trains:

$$
\begin{equation*}
T_{o, p r i o}=n_{\text {prio }} \cdot\left(\bar{t}_{o}+\bar{t}_{s}-\bar{t}_{s, o}\right) \tag{4}
\end{equation*}
$$

| with |  |
| :--- | :--- |
| $n_{\text {prio }}$ | number of prioritized trains, |
| $\bar{t}_{o}$ | mean occupancy time, |
| $\bar{t}_{s}$ | mean service time supplement and |
| $\bar{t}_{s, o}$ | mean service time supplement overlap. |

The time period during which a freight train has to wait before entering a tunnel depends on the priority of passenger trains running in the opposite direction. If the freight and passenger trains had the same priority, the freight train would only have to let passenger trains with an earlier arrival at the tunnel pass ("first come, first serve" principle). The total occupancy time of trains with equal priority

$$
\begin{equation*}
T_{o, e q}=n_{e q} \cdot \bar{t}_{o} \tag{5}
\end{equation*}
$$

is the product of the number of trains with equal priority $n_{e q}$ and the mean occupancy time $\bar{t}_{o}$.

The total occupancy time for freight trains results from the occupancy times caused by equal and prioritized passenger trains. The occupancy time rate $\rho^{*}$ is the ratio of the total occupancy time per investigation period $T$ :

$$
\begin{equation*}
\rho^{*}=\frac{\left(T_{o, p r i o}+T_{o, e q}\right)}{T} \tag{6}
\end{equation*}
$$

| with |  |
| :--- | :--- |
| $\rho^{*}$ | occupancy time rate, |
| $T_{o, p r i o}$ | total occupancy time of prioritized trains, |
| $T_{o, e q}$ | total occupancy time of trains with equal priority and |
| $T$ | investigation period. |

### 3.3 Disturbed and Undisturbed Trains

The occupancy time rate $\rho^{*}$ represents the ratio of the total occupancy time per investigation period for one tunnel. It is assumed that the occupancy time rate $\rho^{*}$ equals the rate of disturbed trains. Thus, the rate of disturbed trains per tunnel $\rho_{t}^{*}$ is known at this point. Given that there are several tunnels on one railway line, obstructions might occur in more than one tunnel. To determine the rate of disturbed trains for a whole line including several tunnels, it is necessary to use probability calculus. Assuming that both directional tracks are uncorrelated, a possible obstruction in tunnel 1 does not affect whether the train is disturbed in tunnel 2.

Formulas for two relevant tunnel blocks are shown in Figure 5. With the known rate of disturbed trains per tunnel $\left(\rho_{t 1}^{*}\right.$ and $\left.\rho_{t 2}^{*}\right)$ it is possible to calculate the rate of disturbed trains in only one specific tunnel ( $\rho_{t 1}$ and $\rho_{t 2}$ ). Accordingly, the rate of trains which are disturbed in both tunnels ( $\rho_{t 1,2}$ ) or in none ( $\rho_{u}$ ) can be determined.


Figure 5: Probabilities of disturbed trains on a line with two tunnels

### 3.4 Blocking Time Modification

The blocking time extensions for freight trains represent the mean time a train has to wait before entering the tunnel in order not to disturb a prioritized passenger train. If the passenger train and the freight train had equal priority, the first train arriving at the tunnel would run first. In that case, the freight train would have to wait for at most the occupancy time $t_{o, i}$ of the passenger train $i$ (see Figure 6). The mean blocking time extension caused by trains with equal priority

$$
\begin{equation*}
\bar{t}_{\text {ext }, e q}=\frac{1}{2} \cdot \frac{n_{e q}}{n_{\text {eq }}+n_{\text {prio }}} \cdot \bar{t}_{o} \tag{7}
\end{equation*}
$$

is the product of the probability of needing to let a train with equal priority pass and the corresponding waiting time $\bar{t}_{o}$. Only the number of trains with equal priority $n_{e q}$ and the number of prioritized trains $n_{\text {prio }}$ are part of the formula since trains with lower priority do not cause disruptions and blocking time extensions are solely considered for disrupted trains.


Figure 6: Maximum waiting time for freight train $f$ caused by passenger train $i$ with equal priority

If passenger trains are prioritized, freight trains must not disturb them. Thus, the freight train needs to let passenger trains, which are already driving through the tunnel and also those which are about to enter the tunnel, pass. The maximum waiting time to let one prioritized passenger train $i$ pass consists of the occupancy time $t_{o, i}$ extended by the operational service time supplement $t_{s}$ (see Figure 7).


Figure 7: Maximum waiting time for freight train $f$ caused by prioritized passenger train $i$

A freight train might have to let several priority trains pass before it can enter the tunnel without disrupting any priority trains. If it has to let more than one passenger train pass, the waiting time lengthens. For each of the expected additional passenger trains $E\left[n_{\text {wait }}\right]$, the waiting time is extended by the passenger trains' mean occupancy time $\bar{t}_{o}$ and the expected buffer times between them $E[b]$. This buffer time is shorter than the time that is needed by the freight train to drive through the tunnel without disrupting prioritized passenger trains. The mean blocking time extension caused by prioritized trains $\bar{t}_{\text {ext,prio }}$ is the product of the probability of letting a certain number of trains pass and the corresponding additional waiting time.

$$
\begin{equation*}
\bar{t}_{\text {ext }, \text { prio }}=\frac{1}{2} \cdot \frac{n_{\text {prio }}}{n_{\text {eq }}+n_{\text {prio }}} \cdot\left(\bar{t}_{o}+t_{S}\right)+\frac{n_{\text {prio }}}{n_{\text {eq }}+n_{\text {prio }}} \cdot\left(\bar{t}_{o}+E[b]\right) \cdot E\left[n_{\text {wait }}\right] \tag{8}
\end{equation*}
$$

| with |  |
| :--- | :--- |
| $n_{\text {prio }}$ | number of prioritized trains, |
| $n_{\text {eq }}$ | number of trains with equal priority, |
| $\bar{t}_{o}$ | mean occupancy time, |
| $t_{s}$ | service time supplement, <br> $E[b]$ |
| expected value for the buffer time $b$ between two prioritized passenger <br> trains for which the freight train needs to wait and |  |
| $E\left[n_{\text {wait }}\right]$ | expected number of passenger trains for which the freight train needs to <br> wait in order to let them pass first. |

The entire mean blocking time extension

$$
\begin{equation*}
\bar{t}_{\text {ext }}=\bar{t}_{\text {ext }, e q}+\bar{t}_{\text {ext }, \text { prio }} \tag{9}
\end{equation*}
$$

consists of the mean blocking time extension caused by trains with equal rank $\bar{t}_{\text {ext,eq }}$ and those caused by prioritized trains $\bar{t}_{\text {ext,prio }}$.

### 3.5 Modification of Minimum Headway Times

The minimum headway times for undisturbed trains remain unchanged whereas the minimum headway times for disturbed trains receive a supplement. The rate of disturbed trains and the blocking time extension for each tunnel are necessary input variables to calculate minimum headway times of disturbed trains. As shown in Figure 8, the blocking time extensions cause the blocking time to begin earlier in tunnel blocks.


Figure 8: Minimum headway time $t_{h, i f, d i s_{-} t 1}$ considering blocking time extensions

In this example, the first block of tunnel 1 is relevant for the modified minimum headway time between passenger train $i$ and freight train $f$. The minimum headway times of undisturbed trains and those of disturbed trains are weighted according to the rate of disturbed trains. For a line with two tunnels the modified minimum headway time $\bar{t}_{h, \text { mod,if }}$ is calculated as

$$
\begin{equation*}
\bar{t}_{h, \text { mod,if }}=\rho_{u} \cdot t_{h, i f}+\rho_{t 1}^{*} \cdot t_{h, i f, d i s_{-} t 1}+\rho_{t 2} \cdot t_{h, i f, d i s_{-} t 2} \tag{10}
\end{equation*}
$$

Variables in this formula are

| $\rho_{u}$ | rate of undisturbed trains, |
| :--- | :--- |
| $t_{h, i f}$ | minimum headway time between trains $i$ and $f$, |
| $\rho_{t 1}^{*}$ | rate of all in tunnel 1 disturbed trains, |
| $t_{h, i f, \text { dis_t1 }}$ | minimum headway time of in tunnel 1 disturbed trains, |
| $\rho_{t 2}$ | rate of only in tunnel 2 disturbed trains and |
| $t_{h, i f, \text { dis_ } t 2}$ | minimum headway time of only in tunnel 2 disturbed trains. |

The formula is extended accordingly if a line includes more or less than two tunnels. With the help of modified minimum headway times, obstructions caused by the prohibition of train crossings can be included when applying the STRELE formula. Longer minimum headway times increase the calculated knock-on delays and therefore decrease the capacity.

## 4 Case Studies

This chapter presents the application of the method to include the prohibition of train crossings in tunnels on two exemplary regional railway lines in order to validate the method's plausibility. The capacity of the lines with and without tunnels is calculated using the described method. Furthermore, the same lines are simulated to evaluate the influence of the prohibition on the operating quality.

### 4.1 Line 1

The 80 km long double-track railway line, which is used for the case study, comprises three tunnels. The shortest tunnel has a length of 650 m and the longest of 1393 m as indicated in Figure 9.


Figure 9: Line 1 and position of double-track tunnels

Table 1: Operating program on Line 1

|  | Tabsenger trains |  | Freight trains |
| :--- | :---: | :---: | :---: |
| Pirection 1 | 47 | 8 | In total |
| Direction 2 | 48 | 7 | 55 |
|  |  |  | 55 |

The operating program, which includes 110 trains per day, is depicted in Table 1.34 of the trains per direction run through tunnel 1 and 2.33 trains in direction 1 and 34 trains in direction 2 use tunnel 3 .

Using the software LUKS ${ }^{\circledR}$ and the method presented in chapter 3, the capacity is determined analytically with and without tunnels. Table 2 shows the results for both directions separately.

Table 2: Capacity in trains per day with and without the prohibition of train crossings

| Line Capacity | Without tunnels | With tunnels | Difference |
| :--- | :---: | :---: | :---: |
| Direction 1 | 71 | 66 | $-7 \%$ |
| Direction 2 | 70 | 67 | $-4 \%$ |

The line capacity of 70 and 71 trains per day declines by 3 to 5 trains per direction when including the prohibition.

In total, the operating program on the existing line includes 55 trains per direction. With as well as without the prohibition of train crossings the capacity exceeds the actual number of trains significantly. Consequently, the line has a moderate utilization rate. The operating quality is respectively high.

Additionally, each scenario is simulated 200 times with the help of the software LUKS ${ }^{\circledR}$. Without considering the prohibition of train crossings, the simulation results in a total delay of 56 minutes per day. When including the prohibition, the total delay increases by 6 minutes (Table 3).

Table 3: Total delay in minutes per day with and without the prohibition of train crossings

| Total delay | Without tunnels | With tunnels | Difference |
| :--- | :---: | :---: | :---: |
| Both directions | 56 | 62 | $+11 \%$ |

### 4.2 Line 2

The second examined line is an approximately 100 km long double-track railway line with one 698 m long tunnel (see Figure 10).


Figure 10: Line 2 and position of the tunnel

Table 4: Operating program in the tunnel on Line 2

|  | Passenger trains | Freight trains | In total |
| :--- | :---: | :---: | :---: |
| Direction 1 | 36 | 23 | 59 |
| Direction 2 | 34 | 24 | 58 |

The operating program is depicted in Table 4. In total, 117 trains of which 47 are freight trains are scheduled to drive through the tunnel.

Using the software LUKS ${ }^{\circledR}$ and the presented method, the capacity is determined analytically with and without the prohibition. Table 5 shows the results for both directions separately.

Table 5: Capacity in trains per day with and without the prohibition of train crossings

| Line Capacity | Without tunnels | With tunnel | Difference |
| :--- | :---: | :---: | :---: |
| Direction 1 | 111 | 106 | $-5 \%$ |
| Direction 2 | 97 | 97 | $0 \%$ |

The line capacity in direction 1 declines from 111 to 106 trains per day, which means by 5 trains when including the prohibition in the tunnel. The minimum headway times on the tunnel's line section are extended by the prohibition of train crossings. For the whole line though, another section is relevant for the decisive minimum headway time that leads to unchanged line capacity in direction 2.

Without considering the prohibition of train crossings, the simulation results in a total delay of 87 minutes per day. When including the prohibition, the total delay of all trains increases by 3 minutes (Table 6). Since the line has only a low utilization rate, the effects on the operating quality by the prohibition are rather low.

Table 6: Total delay in minutes per day with and without the prohibition of train crossings

| Total delay | Without tunnels | With tunnel | Difference |
| :--- | :---: | :---: | :---: |
| Both directions | 87 | 90 | $+3 \%$ |

### 4.3 Evaluation

It can be seen that with the modified analytical method as well as with simulations, the prohibition of train crossings in tunnels reduces the line's operating quality. Corresponding to the low utilization rate of the examined lines, the simulation shows only a slightly increased delay caused by the additional obstruction. The analytical method also shows a slight deterioration of the capacity.

A comparison of the results from the analytical method and from simulations is only possible to a limited extent. One specific timetable on each of the two lines has been used for simulations. Changes in the timetable such as different arrival and departure times will change the results. However, this does not affect the results of the timetable-independent analytical method. Thus, the case study is incapable of proving that the presented method reproduces the impact of the prohibition perfectly, but it still validates the plausibility of the results. The results of the simulations and analytical method show similar relative changes of the capacity and the total delay.

The presented method is going to be implemented in the software LUKS ${ }^{\circledR}$. Since this will reduce the calculating time significantly, it will easily be possible to calculate the effect on a larger number of generic and existing railway lines, including those with high traffic loads.

## 5 Conclusions

This paper presents a new method to include the prohibition of passenger and freight train crossings in double-track railway tunnels by modifying blocking times of disturbed trains. The blocking time extensions represent the mean time a train has to wait before entering the tunnel in order not to disturb a prioritized train. Changes in blocking times influence minimum headway times, which are input variables for the capacity calculation. The extent as to which the prohibition of train crossing in tunnels influences line capacity is shown in a
case study based on the STRELE method. Longer minimum headway times caused by the infrastructure constraint increase knock-on delays and thereby reduce the capacity. This gives the opportunity to calculate the effects the prohibition of train crossings in tunnels has on line capacity and thereby helps to improve the results of analytical methods. The exemplary application of the presented method on two railway lines validates the plausibility of the results. After being implemented in the software LUKS $^{\circledR}$, the method can easily be applied on numerous lines with different operating programs to make sure the results are also plausible for these scenarios.

## 6 References

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