Operational effects of driverless trains on secondary lines

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Abstract
The operation of railway systems depends in particular on infrastructure and vehicle data. A major challenge is the implementation of driverless operations. For many years, an unattended train operation has represented the state of the art for closed systems, e.g. in metros. Due to other parameters and constraints, e.g. requirements for vehicles, the situation in railway differs: operating without a driver is impossible in most cases. However, technical developments create new opportunities regarding driverless trains in railway operations. This results in differences compared to conventional trains.

In the present paper we aim to analyze the effects of driverless railway operations on different lines. Due to vehicle characteristics, an operation with driverless trains seems to be convertible initially on secondary lines. Such lines are often characterized by long block sections between stations, limited speed and often a single line. Our main focus are effects on headway times and practical capacities in different scenarios. Therefore, some assumptions of driverless trains are necessary, e.g. changes in braking curves, which have an impact on railway operations research studies. Furthermore, we make two main assumptions for driverless trains on secondary lines: Firstly, maximum speed of driverless trains is set at 70 km/h due to driving on sight. This speed limit is justified in many references and should enable a safe operation with the technical equipment of those trains as track monitoring is performed by the trains. Secondly, the new technical equipment of driverless trains, e.g. radio systems, enables shorter headway times, which is comparable with moving blocks. Driverless operating trains could lead to less delays than present trains with drivers because of the more uniform driving. This allows a more precise planning of operations with effects on the practical capacity. The results show the potential of driverless trains on secondary lines. Generally, driverless trains allow new operational concepts, e.g. a service on-demand for demand-oriented rides. In addition, an outlook on how the analyses can be extended is provided.

Keywords
driverless operation, GoA, capacity, headway time, simulation

1 Introduction

Driverless driving is becoming more and more important across all modes of transport. The initial situation of driverless vehicles varies between the modes of transport. Flights with autopilots and unattended airplanes have been technically possible for many years (Keane et al. (2017)). In road transport, there is also a trend towards driverless driving or platooning, in which several vehicles are controlled by one driver (Shladover (2016)). In general, driverless driving in road transport has a high media impact. The initial situation in railway is different: trains also use many technical systems to reach a very high safety level, for example different train control systems or the driver´s safety device (Janicki (2018)). In addition, technical systems lead to further advantages, e.g. a higher capacity. However, a driver is still an important component of railway operations.

New technical developments allow changes in the current system of railway operations: an operation with driverless trains and the associated waiver of a driver seems to be convertible as in metro systems. First test drives with drivers only on-board as fall-back level give cause to be hopeful for an area-wide spread of driverless operations (Editor Signal+Draht (2020)). Due to technical equipment and system properties of railway, in particular the long braking distance, a driverless operation by driving on sight is predestined on secondary lines for speeds up to 70 km/h. This speed limit is endorsed in many references for driverless operation on secondary lines in Germany (Flamm et al. (2019); Meyer zu Hörste (2017); Schindler (2019); von Stillfried and Schindler (2020)).

Such low speed limits are normally given on secondary lines. Those lines are suitable for operations with driverless trains (von Stillfried and Schindler (2020)). The technical on-board equipment guarantees a safe operation, e.g. a track monitoring by cameras and sensors, and can adapt speed to local conditions and deviations. Furthermore, secondary lines are characterized by long block sections and a single line. On the one hand, the effects of driverless driving are to be analyzed on a generic single-track line according to (DB Netz AG (1999)) with different train types and different train control systems. On the other hand, a double-track line is analyzed additionally. Those results allow a comparison between the different tracks and operational effects. The paper provides a better understanding of the benefits of driverless trains. It is possible to use driverless vehicles in high-speed traffic as well. However, high-speed lines and secondary lines differ significantly. On high-speed lines ATO systems with track vacancy messages are usually installed. Therefore, another framework is given and is not comparable with our work (Yin et al. (2017)).

Chapter 2 gives an overview of railway capacity. It includes amongst other things the major meaning of the blocking time, analytical methods and advantages of driverless trains. Chapter 3 presents a method on how to include driverless trains in railway operations. The implementation and results of this method are described in chapter 4. Chapter 5 summarizes the findings of the present work and gives an outlook on further research.

2 Railway capacity

The rail mode of transport is characterized by long braking distances due to the low coefficient of friction between steel wheels and steel rail tracks. In order to be able to guarantee safe railway operations, a railway line is usually divided into block sections. Only one train at a time can occupy a block section. First, this chapter gives an overview about the blocking time. Subsequently, the meaning of analytical methods in railway is explained. Finally, the advantages of driverless vehicles in railway are stated.

2.1 Blocking time and its effects on railway operations

Rail-guidance and long braking distances are the main system properties of railway operations. Therefore, special security measures are necessary (Theeg and Maschek (2019)). Depending on the permitted speed and other factors, certain safety criteria are required (Stanley (2011)). In contrast to other modes of transport, trains run usually in block sections. There is only one train allowed in one block section, which could have a length of several kilometers and have an impact on the capacity (Pachl (2005)). To investigate the capacity consumption blocking times are relevant. The blocking time of a block section does not only consider the actual time of a train in the viewed block section, but consists of the following six time elements (Pachl and White (2004)):

- Blocked time before running through the viewed block section:
  ① time for clearing the signal ② signal watching time ③ approach time.
- Blocked time while driving through the viewed block section:
  ④ time between block section signals.
- Blocked time after driving through the viewed block:
  ⑤ clearing time ⑥ release time.

The sum of those six time elements is the blocking time of a block section, which is illustrated in Figure 1. Some deviations of the blocking time theory are possible because they depend on the train control and signalling systems (Wendler (2009)).

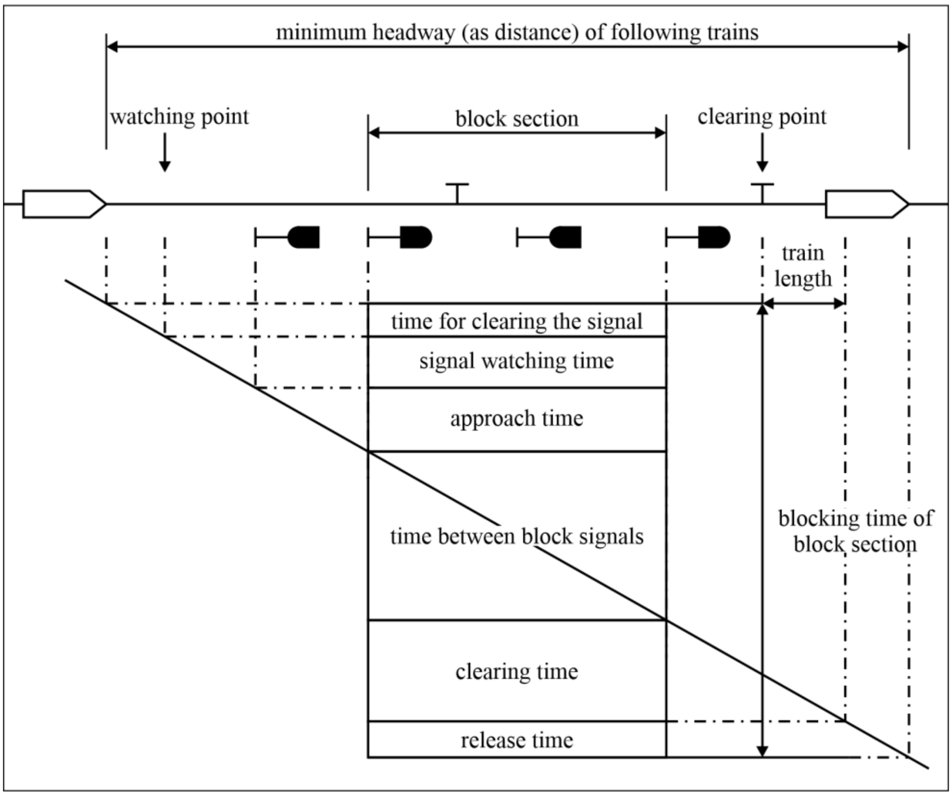

Figure 1: Blocking time of a block section (Pachl (2000))

Figure 1 illustrates the blocking time of one block section. The blocking time of each block section can vary as it depends on many aspects, e.g. the length of each block section or the permitted speed. The totality of occupied infrastructure during a train ride is the so-called “blocking time stairway” (Janicki (2018)). It can be determined for every train path of a given timetable (Bešinović and Goverde (2018)). Using blocking time stairways conflicts with other trains on the same infrastructure may be identified, so that solutions must be constructed, e.g. an additional stop for operational reasons (DB Netz AG (2018)).

With the blocking time stairways, it is also possible to determine the minimum headway time between two trains on a common path without overtaking possibilities (Pachl (2020)). The minimum headway time can be read off at the beginning of the common path between two overtaking possibilities. For this purpose, the blocking time stairways of the two succeeding trains are pushed together until they touch, but do not overlap (Hansen and Pachl (2014)). If they overlapped, the timetable would not comply with guidelines because of an unallowed occupation conflict. In addition, timetables contain time surcharges for each train and buffer times between blocking time stairways (Weymann and Nießen (2015)). Running time surcharges reduce the delay of each train. Normally, timetables contain running and stopping time margins and engineering allowances (Pachl (2014)). Buffer times reduce the transmission of train delays on the following trains (Goverde and Hansen (2013)).

Figure 2 illustrates the coherences between the blocking time and the minimum headway time. The time-distance graph shows two trains driving with a different speed between two stations. Train 1 is slower than train 2, which is seen by the height of each block section. When the minimum headway time is kept when leaving the station on the left, the second train can run without a stop for operational reasons between the stations.

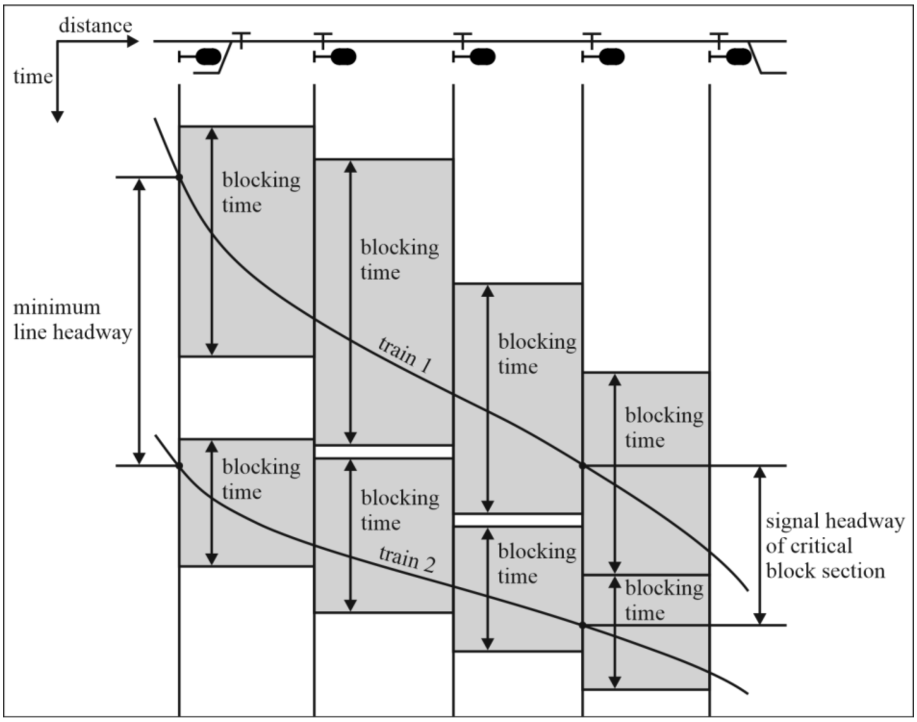

Figure 2: Minimum headway time (Pachl (2020))

Timetables do not take delays into account. Disturbances on the trains, the infrastructure and others can cause delays on the trains, which have effects on the operations (Rusdiansyah and Iswardani (2018)). Railway companies differ between various delay types within an observation space. The main types of delays are

- the entry delay (delay of a train while running in the observation space),
- the primary delay (suffered delay in the observation space) and
- the knock-on delay (delay resulting because of connection, occupation and rostering conflicts in the observation space). (DB Netz AG (2009)) (Weik et al. (2016))

2.2 Analytical method STRELE

Several types of analytical methods are used in railway operations research, in particular construction, simulation and analytics (Salido et al. (2012)). (Lindfeldt (2010)) gives an overview of various methods and distinguishes between different characteristics of the lines, e.g. single-track and double-track lines. The given methods vary between further properties, too. (Higgins et al. (1997)) describe a solution to find the best number and positions of crossing stations for high-speed trains on single-track lines with a timetable.

As described in section 2.1, railway companies differ between various delay types within an observation space. The different delays lead to an unscheduled waiting time during operation. The entry delay is composed of the probability of an entry delay and the mean entry delay of delayed trains (see Figure 3).

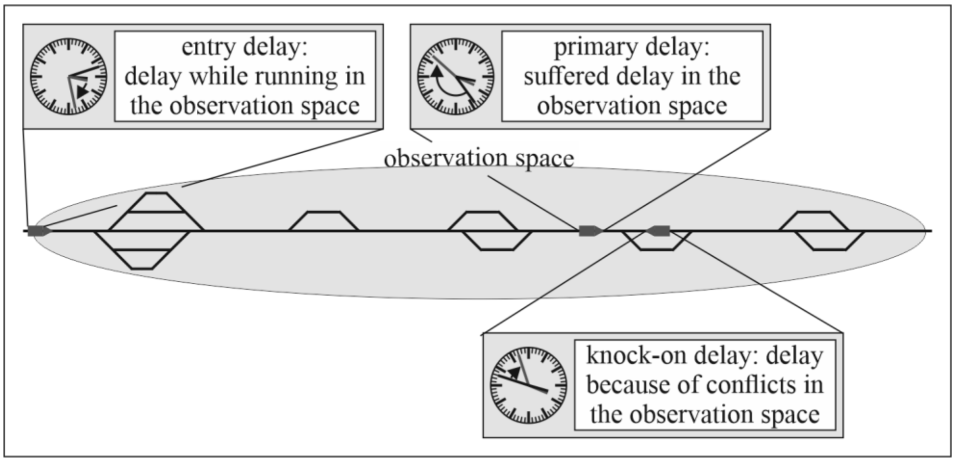

Figure 3: Different types of delays

In railway operations, many trains might be delayed. Delayed trains have a negative impact on the quality of the rail transport service (Grechi and Maggi (2018)). Therefore, it is more important to consider delayed trains in analyses. Delays can vary each day, but only by their consideration realistic operations can be described. (Schwanhäußer (1974)) created the first model for railway capacity analysis with delay distributions. The results led to the STRELE formula to determine the knock-on delays within an observation space. Other methods and tools were created in the following years (Schwanhäußer (1994)). Individual tools also differ between several countries. A discussion about the capacity analysis of railway lines in Germany can be found in (Weik (2016)).

One software tool for railway capacity assessment is LUKS®, which is based on the STRELE formula (Janecek and Weymann (2010)). LUKS® is one of the standard tools for capacity calculations in Germany and is applied by German Railways (DB Netz AG (2018)). LUKS® performs railway capacity calculations for both single- and double-track lines. The STRELE formula determines the knock-on delay $\overline{K}$ within the observation space. The STRELE formula is as follows

$$\overline{K}=\left(p_{del}-\frac{p_{del}^{2}}{2}\right)\cdot\frac{\overline{t}_{del}^{2}}{\overline{b}+\overline{t}_{del}\cdot(1-e^{-\overline{t}_{h}/\overline{t}_{del}})} \cdot\left[p_{eq}\cdot(1-e^{-\overline{t}_{h,eq}/\overline{t}_{del}})^{2}+\left(1-p_{eq}\right)\cdot\frac{\overline{t}_{h,diff}}{\overline{t}_{del}}\cdot\left(1-e^{-2\overline{t}_{h,diff}/\overline{t}_{del}}\right)+\frac{\overline{t}_{h}}{\overline{b}}\cdot(1-e^{-\overline{t}_{h}/\overline{t}_{del}})^{2}\right]. \tag{1}$$

The input parameters for the STRELE formula are

p_{del}	probability of an entry delay
$\overline{t}_{del}$	mean entry delay of the delayed trains
$\overline{b}$	mean buffer time
p_{eq}	probability of two trains with the same rank
$\overline{t}_{h}$	mean minimum headway time
$\overline{t}_{h,eq}$	mean headway time between two trains with the same rank
$\overline{t}_{h,diff}$	mean headway time between trains with a different rank

A defined level of service is a basis to get the optimal quality in operation. Admissible knock-on delays $adm\sum K$ are defined in (DB Netz AG (2009)) as

$$adm\sum K = T\cdot q\cdot 0{,}260\cdot e^{-1{,}3\cdot ptr}. \tag{2}$$

The input parameters are

T	observation time
q	quality factor ($q = 1$ for optimal quality)
ptr	ratio of passenger trains

By applying formula (1) and (2), the minimum required buffer time $\overline{b}_{req}$ can be calculated. Finally, the corresponding number of trains n_{opt} is calculated by the following formula (Schwanhäußer (1974))

$$n_{opt}=\frac{T}{\overline{t}_{h}+\overline{b}_{req}}. \tag{3}$$

In summary, many input parameters influence the analytical methods and finally the capacity of lines. The different delays on each day have a disparate influence on operations, too. Therefore, plausible assumptions respectively input parameters have to be met.

2.3 Advantages of driverless vehicles in railway operations

In comparison to the conventional railway vehicles, driverless operations include many advantages for the participants, e.g. for the passengers, the railway transportation and operating companies. Main advantages of the automation are the effects on safety, a service on-demand and the energy efficiency. Figure 4 gives an overview of the main advantages of driverless vehicles in railway operations (Wang et al. (2016)). Furthermore, driverless trains allow a more uniform driving than present trains with a driver in the cab. This allows both a more precise planning of operations and a higher reliability to comply with the timetable. This advantage leads to a higher practical capacity because driverless trains can drive with less speed deviations from the permitted speed than conventional trains. They can easily customize their speed in each situation. In addition, a driverless operation is protected against sicknesses and strikes of drivers, which already led to train failures in the past. This enables a higher reliability, too. But driverless operations also have some disadvantages (Bruckner (2019)). Instead of sickness and strikes of the drivers, the system could be a target of cyberattacks. Such attacks could stop the operation immediately and would deteriorate the trust in the system. Furthermore, an operation with malfunctions, e.g. infrastructure problems, and the integration of level crossings are significant examples for the challenges.

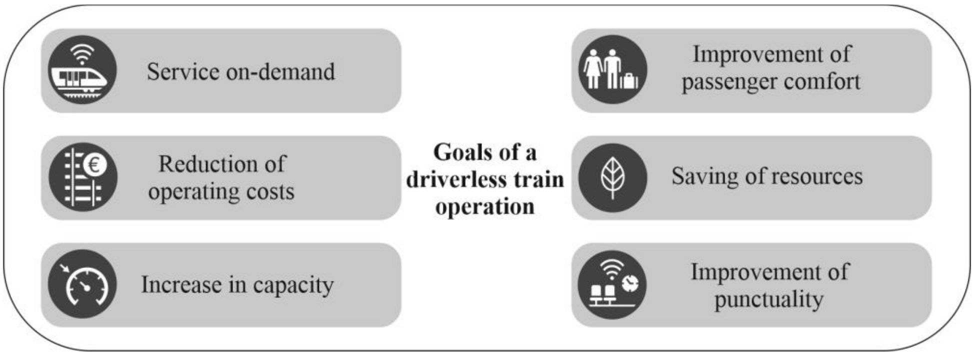

Figure 4: Goals of a driverless train operation

For many years, the state of the art in metro systems around the world has been allowing an unattended train operation with no staff on-board (Powell et al. (2016)). The metro systems differ from railway systems in some technical, operational and legal basics. Metro systems are usually characterized by a closed system without interactions with the environment, similar track sections and similar vehicles for passenger transport. One company operates as an infrastructure and rail transport company in one (Pollmeier and Schneider (2015)). However, metro systems demonstrate that driverless operations are possible for rail-guided traffic.

In current railway operations, train drivers are essential in most cases. They are supported by different technical systems to ensure a safe operation. The use of such technical system depends on various factors, for example the maximum speed of the line. Because of the system properties of railway systems, the rail-guided traffic is predestinated for an automatic operation (Nießen et al. (2017)). Depending on the technical design of the infrastructure and trains, a distinction is made between different Grades of Automation (GoA) (IEC 62290-1:2014):

- GoA 0 – On-sight: Driving on sight with no automatic train protection.
- GoA 1 – Manual: Manual driving with an automatic train protection.
- GoA 2 – Semi-automatic: Train is driven automatically with a driver in the cab.
- GoA 3 – Driverless: Automatically driven trains with a driver on-board.
- GoA 4 – Unattended: Completely driverless operation.

GoA 2 corresponds to the current state of the art in railway operations. Therefore, a driver is needed in the cab. Higher grades of automation are explored in some test lines and are used in special lines, for example for mining trains in Brazil and Australia (Gralla (2016)). In summary, a driverless operation is also possible in railway. Some aspects still have to be clarified, but the basic feasibility is given. It seems to be a question of time until driverless trains are part of railway operations.

The advantageousness of a driverless operation differs between railway lines. Lines have different characteristics, in particular different speed limits. The speed limits and other criteria have an impact on the vehicles. In our paper we focus on simple equipped lines and refer them as secondary lines. Duo to many interactions on secondary lines, e.g. level crossings, and the legal framework, such lines often allow a maximum speed of about 80 to 100 km/h for conventional trains.

When the driver is renounced, driverless vehicles need a special technical design for checking the track, e.g. cameras (Schindler (2019)). In combination with the system properties and long braking distances, driverless operations on secondary lines are predestined for a speed up to 70 km/h in Germany, which many references endorse (Flamm et al. (2019); Meyer zu Hörste (2017); Schindler (2019); von Stillfried and Schindler (2020)). Up to the speed limit of 70 km/h, driving on sight seems to be convertible with both the existing technology, e.g. sensor technology, and the infrastructural features of secondary lines. The technology has to ensure a safe operation for driving on sight. Driverless trains have to observe the route and they have to adjust their speed. A driverless operation with higher speed would be possible, if the line is more technical equipped (e.g. ATO over ETCS).

The proposed speed limit for driverless trains depends by driving on sight on visibility and braking ability. Overall, many factors, e.g. vehicle factors, infrastructure or weather, affect braking distance. In comparison with conventional trains, reaction time by driverless trains is neglected because of the technic. However, an exact calculation of braking distance is difficult to perform. Due to many factors, we make a simplified calculation. The braking distance in driverless operations is about 200 m long (see formula (4) and (5)). In order to react in time, driverless trains have to “see” the next 200 m of the path or otherwise adjust their speed.

$$a_b = g \cdot \mu = 9{,}81 \frac{m}{s^2} \cdot 0{,}1 = 0{,}981 \frac{m}{s^2}. \tag{4}$$

With

a_b	mass-independent braking deceleration
g	gravitational acceleration
μ	coefficient of static friction

This result is necessary to calculate the braking distance. The value of a_b is comparable with the nominal emergency brake deceleration between 0 and 70 km/h using ETCS braking curve model for a passenger train (ERA (2021)).

$$s = \frac{v^2}{2 \cdot a_b} = \frac{\left(\frac{70}{3{,}6}\right)^2 m^2 \cdot s^2}{2 \cdot 0{,}981 m \cdot s^2} = 192{,}7\ m \approx 200\ m. \tag{5}$$

With

s	braking distance
v	speed

3 Method

Railway infrastructure and lines are characterized by their uniqueness. Almost every line has its peculiarities. Lines differ in the maximum speed, the distances between stations, timetables, etc. Those different properties make general statements regarding performance and other aspects difficult. Railway infrastructure is very expensive and durable. Therefore, a cost-effective and high-performance infrastructure must be planned for new lines or expansions of lines. Thereby, the individual lines have other influences on the capacity.

First, this chapter gives an overview of the different standard lines in Germany. As driverless operations appear to be feasible on secondary lines, the special requirements of those lines will be met. Afterwards, the effects of driverless operations will be described. Thereby, some assumptions are necessary to include driverless trains in current railway operations.

3.1 Determination of input variables

Railway operations research studies are a useful tool for getting information about lines, e.g. their capacity. Driverless operations also have an effect on lines and their capacity due to other train characteristics compared to conventional trains. Analyses of each line are very time-intensive. Therefore, first analyses should be carried out on standard generic lines. DB Netz AG, the railway infrastructure company in Germany, uses different standard lines as basic lines, which vary in their characteristics (DB Netz AG (1999)). The main differences between the standard lines are listed hereafter:

- Target speed: The long-term planning speed, e.g. 250 or 100 km/h.
- Optimization criteria: Main use of the line, e.g. for local public transport or rail freight transport.
- Operating program: Upper limit of the number of trains in each direction on each day.

Those different standard lines influence the trains and vice versa. The choice to operate with driverless trains is set by a maximum speed of 70 km/h (compare formula (4) and (5)). Therefore, the single-track standard line R 80 is chosen as an example line (see Figure 5).

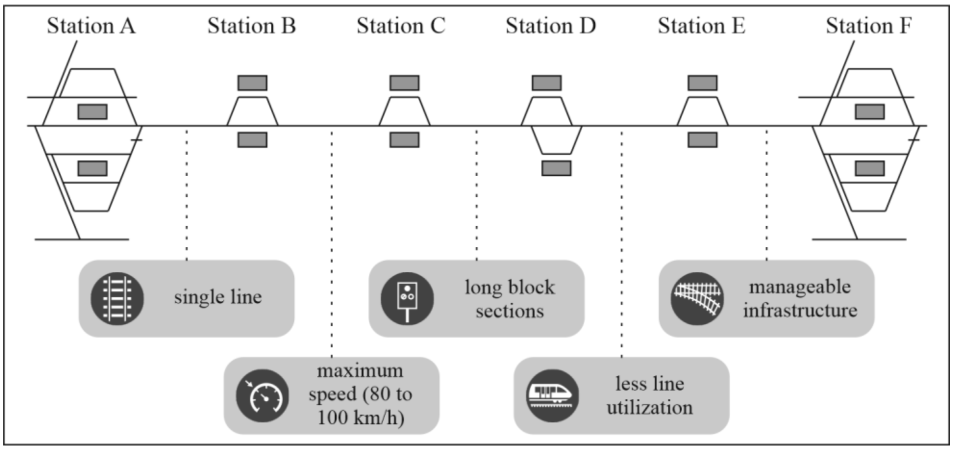

Figure 5: Characteristics of the standard line R 80 (according to DB Netz AG (1999))

The main characteristics of the standard line R 80 are given in Figure 5. Essential characteristics are the target speed up to 100 km/h, a single line, a traffic volume up to 50 trains on each day and the length of the block sections. A block section is from one station to the next station, which can be up to 20 km long. Furthermore, most of the stations are crossing stations with only one or two tracks for overhauls. Those characteristics lead to a limited operating program. Nevertheless, such lines do not have many capacity reserves during a day. The long block sections distances have a negative impact on the capacity. This means the total number of trains that can traverse the railway line in a given period of time is very small (Mussone and Calvo (2013)). The capacity is influenced by many factors, e.g. the speed of the trains or the length of the block sections. Capacity reserves are normally given at off-peak hours and at night because the operation is discontinued.

To compare the results of the single-track line, we also analyze a double-track line. This line is similarly structured to the standard line R 80. The main difference is the presence of a second line between the stations. Stations, which are about 20 km apart from each other, have got four tracks. This structure enables overhauls in both directions.

Railway operations research studies contain certain parameters for the delay distributions of the trains (Yang et al. (2019)). The values differ among different train types, e.g. local public transport or rail freight transport, and among the load on the feeder lines. This results in different probabilities as well as average values of the delayed trains (DB Netz AG (2009)).

3.2 Impact of driverless trains

An operation with driverless trains enables new possibilities for railway systems. In comparison to conventional trains, driverless trains differ in operational, legal and other aspects (see section 2.3). As driverless trains do not exist in railway yet, some assumptions for operation are required. The main assumption for this paper belongs to the maximum speed of driverless trains on secondary lines. In combination with the technical possibilities, it is assumed that driverless trains cannot run faster than 70 km/h (see section 2.3). For higher speeds driving on sight for driverless trains is not practical. Due to characteristics of secondary lines, speed differences between conventional and driverless trains are manageable. Conventional trains can run with maximum speed of such lines, which is normally up to 80 or 100 km/h, while speed of driverless trains is technically limited for driving on sight. This assumption leads to operational restrictions. Furthermore, driverless operations enable better realizations of the permitted speed on a line. It can be expected that driverless trains run more evenly than conventional trains.

The principles of train separation depend on the infrastructure and the trains. Most lines are divided into block sections. Trains can only follow each other in fixed section distances. In derogation of this, driverless trains make driving in moving blocks easily possible due to their technical equipment. Moving blocks enable a minimum safety distance between following trains (comparable with ETCS Level 3 – (Stanley) (2011)). A change of the train control system will have a great impact on the operation. The reduction of blocking times for moving blocks is illustrated in Figure 6 by the comparison of blocking times between fixed block sections and moving blocks. We can state large differences in blocking times between driving with long fixed block sections and driving with moving blocks.

To increase capacity on secondary lines, either block sections have to be shortened or an operation with moving blocks has to be implemented (we do not consider other infrastructural modifications, e.g. a double-track line expansion). Driverless trains need technical on-board equipment anyway. Therefore, they can be equipped with additional technology to realize driving in moving blocks on sight. These kinds of moving blocks can be realized while driving in one direction. Among other things, secondary lines are characterized by single-track lines. Therefore, deadlocks must be prevented. Trains from different directions only can cross in crossing stations. To prevent deadlocks, crossing trains must wait in a station until the line is cleared. The restriction must be ensured, for example by communication with a control center or between the driverless vehicles themselves.

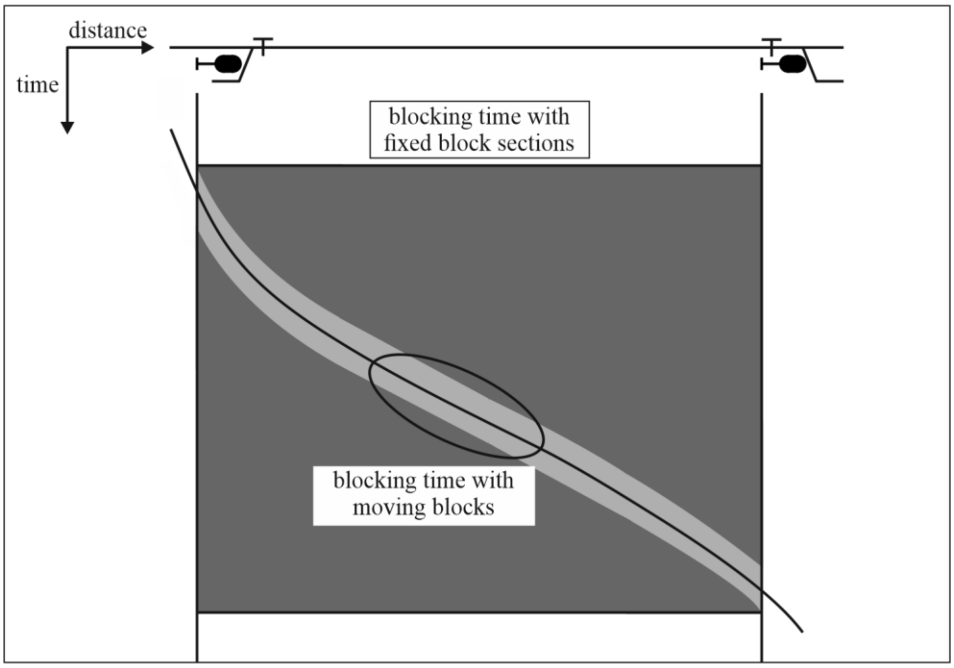

Figure 6: Differences between the blocking times

Driverless trains differ from conventional trains in some technical vehicle features and they can particularly realize uniform driving. It means the velocities and speed profiles of driverless trains are relatively similar and have little variance. The uniform driving has a positive effect on both the timetable planning and the operation. Thereby, an exact planning with only small deviations is possible, e.g. because of weather influences. Furthermore, the driverless trains can adjust their speed with regard to the current situation. In comparison to conventional trains, the driverless trains either need a connection to other trains, to interlockings or to both. Thereby, a predictive driving is actionable with a more global view.

All aspects of the driverless trains could lead to less delays and have positive effects on performance measures. A demonstration of these assumptions is roughly realizable with software tools. The service on-demand is visually displayable with exemplary train paths.

4 Case study: Operation with driverless trains

In the following, we analyze the operational effects of driverless driving in comparison to conventional trains. First, the input variables for the two lines and the procedure are described. We analyze different scenarios, e.g. different permitted velocities of the lines and trains. Subsequently, the results with effects on the operation are explained.

4.1 Input variables and procedure

Input for a timetable are infrastructure data, information on the rolling stock and the operation. The data can vary on each line. First, the single-track line for a secondary line (R 80 – see Figure 5) is used as foundation to analyze the operational effects of driverless driving. Figure 5 contains the essential characteristics of the line. There is not the same speed limit for every section, but the maximum infrastructure speed varies between the sections. However, the speed profile has a magnificent effect on the results of driverless operations. While driverless trains are cut at 70 km/h, conventional trains can drive faster. This difference affects the results of the timetable construction. Figure 7 describes the track layout of the case study with the maximum infrastructure speed. The figure shows the speed profile along the individual sections. The speed limits vary between 40 and 100 km/h on the 100-kilometers-long line. Every block section starts in a station and ends in the next station. Therefore, each block section is about 20 kilometers long. All trains have to stop at each of the six stations for 0.6 minutes.

The second analyzed line, a double-track line, is similarly structured to the line in Figure 7, e.g. with the same speed profile. The difference is a second line between the stations, which enables direction-specific operations.

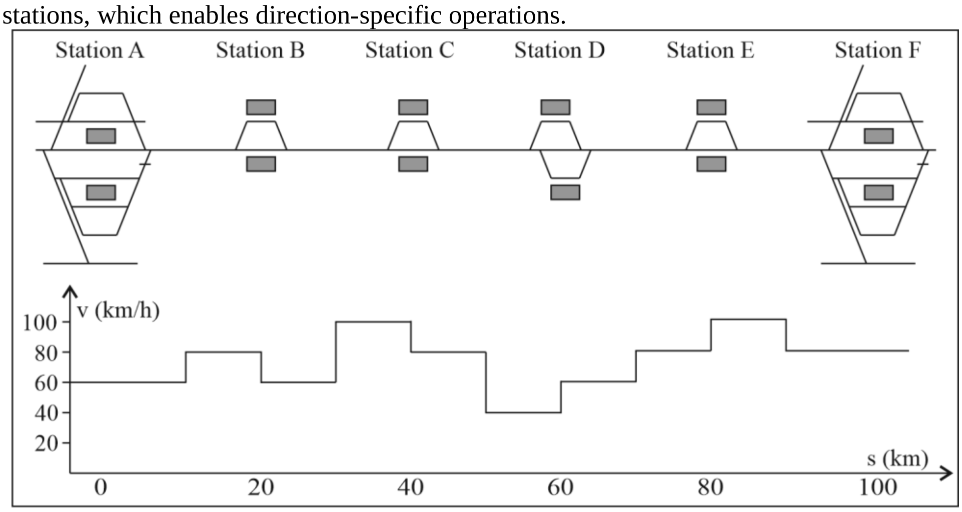

Figure 7: Track layout of the single-track line R 80

In addition to infrastructure data, rolling stock data is necessary for the runtime calculation and the timetable construction. For the investigation, the same vehicle is used for both the conventional trains and the driverless trains in order to get comparable results. The vehicles should be diesel railcars because secondary lines are often non-electrified lines. Depending on the scenario, the trains use different train control systems and differ in their maximum speed. A comparison between different vehicle scenarios and a stepwise transition from conventional to driverless operations can be made. The differences between the two train types used are given in Table 1. The maximum speed of driverless trains depends on technical conditions. Conventional trains drive in fixed block sections, whereas driverless trains drive in moving blocks. Thus, the main technical difference between those train types are the maximum speed and the used train control system. Furthermore, the data of driverless trains vary in comparison to the train data of conventional trains to consider the advantages of driverless operations (see section 2.3). One example is the braking curve.

Another example is the point to reduce the permitted speed. If there is a speed reduction given for entering a station, conventional trains have to reduce their speed at the main signal, which could be a few hundred meters in front of the next switch. In contrast, driverless trains have to reduce their speed only a certain distance in front of the speed-limited switch. This enables a longer path with higher speed as driverless trains do not need main signals for their operation. In summary, operation with driverless trains allows new procedures with great impacts on operation.

Table 1: Comparison of the train types

Characteristic	Conventional trains	Driverless trains
Maximum speed	140 km/h	70 km/h
Headway	Fixed block sections	Moving blocks

The two lines (single- and double-track line) and the two train types (conventional and driverless trains) are the basis of the case study. Different scenarios are created, e.g. different speed profiles of the lines and the trains, to determine the effects on operation. Table 2 illustrates the considered scenarios, which we analyzed. Each scenario is evaluated for operation with only conventional or driverless trains as well as a mixed operation with conventional and driverless trains. Furthermore, for the basic scenario an operation with moving blocks by conventional trains is investigated, too.

Table 2: Considered scenarios

Scenario	Permitted speed (km/h)		Single-track line	Double-track line
	line	conventional / driverless trains		
I. Basic	40-100	100 / 70	✓	✓
II. Reduced speed of the line	40-60	100 / 70	✓	✓
III. Reduced speed of the driverless trains	40-100	100 / 60	–	✓
IV. Shorter block sections	40-100	100 / 70	–	✓
V. Changed entry delay	In each scenario		✓	✓

4.2 Results of the operational effects

In the following, we describe the results of the different scenarios on each line with conventional and driverless trains. These results include running times, headway times and the practical capacity. Operations with conventional trains represent the current situation with a driver on-board.

All results in this paper are based on conflict-free timetables. In general, timetable construction on double-track lines is much easier as there are no conflicts between trains in different directions. Restrictions only result from driving in fixed block sections or in moving blocks. The long block sections and the single-track line of the example line R 80 make the construction of a conflict-free timetable with conventional trains very difficult. Furthermore, opposing move protection has to be considered on single-track lines, which aggravates timetable construction.

First, the results of running times are presented in Table 3 [all time calculation have been performed with LUKS® version 3.1.1]. Table 3 includes running times from station A to station F for both lines and the scenarios with conventional and driverless trains. The running times represent the technical running times and depend on infrastructure, e.g. reduced speed of a line, and considered trains in a scenario. Table 3 does not include scenario V because changed entry delays do not have impacts on running times.

Table 3: Relevant running times: direction station A to station F

Scenario	Single-track line		Double-track line	
	conventional trains	driverless trains	conventional trains	driverless trains
I. Basic	1:35:42	1:43:10	1:35:42	1:43:10
II. Reduced speed of the line	1:53:13	1:51:19	1:53:13	1:51:19
III. Reduced speed of the driverless trains	–	–	1:35:42	1:51:23
IV. Shorter block sections	–	–	1:35:42	1:43:10

The results in Table 3 show that running times are impacted by permitted speeds of both the infrastructure and vehicles. In such scenarios, trains need more time for driving from the beginning to the end station, but the length of a block section does not impact running times. Furthermore, the running time does not depend on the number of tracks of lines. It does not matter if lines consist of single- or double-track lines as the running time describes the fastest duration for driving between the beginning and the end of the considered line. As the differences between the two given directions are very small, the results of the other direction are not presented in the table.

An important result shows scenario II with permitted speed reductions of the lines to 60 km/h meaning that both conventional and driverless trains are not allowed to drive faster than 60 km/h on the one hand. But on the other hand, both train types reach the maximum speed of the lines. In this case, the running times of driverless trains are lower than those of conventional trains. This is due to better vehicle data of driverless trains as described in the assumptions for operation.

To summarize the results of this analysis, running times of conventional and driverless trains are similar in both directions. The running time does not depend on the length of block sections, but on the maximum speed of the lines and trains. The lower the speed, the more attractive becomes driverless operation by driving on sight.

In the following, we describe the effects on the headway time. All headway times are similar in both directions. Therefore, Table 4 includes the results of the direction from station A to station F, which is comparable with the results in Table 3. Headway times on single-track lines contain a special feature: not only the successive move protection has to be considered, but also the opposing move protection. Therefore, the results in Table 4 are different for following and crossing train movements of driverless trains on the single-track line because they drive in moving blocks. Driving in the same direction, they can follow in moving blocks. Driving in the opposite direction, the whole single-track line needs to be free. This separation is not necessary for conventional trains. Due to driving in fixed block sections, the times for following and crossing train movements are similar. The results of mixed operation are not presented in Table 4. In mixed operation, varying train sequences are possible. This has effects on headway times. The headway times for the train sequences driverless train-driverless train and conventional train-conventional train are listed in the following table. The other two train sequences conventional train-driverless train and driverless train-conventional train are comparable with the train sequence conventional train-conventional train. In the basic scenario, the results for headway times of conventional trains driving in moving blocks are comparable with driverless trains. Table 4 does not include scenario V because changed entry delays do not have impacts on headway times.

Table 4: Relevant headway times: direction station A to station F

Scenario	Single-track line		Double-track line	
	conventio-nal trains	driverless trains[1]	conventio-nal trains	driverless trains
I. Basic	23:09	1:06 / 23:47	22:53	1:04
II. Reduced speed of the line	25:33	1:06 / 25:11	25:16	1:04
III. Reduced speed of the driverless trains	–	–	22:53	1:04
IV. Shorter block sections	–	–	9:19	1:04

[1] following train movements in the same direction / crossing train movements

The results show that headway times of driverless trains between the scenarios in the same direction are always similar. This means moving blocks are always equal and do not impact headway times. On single-track lines, the headway time of crossing train movements is noticeable. Driverless trains have to wait very long until the line is free. The waiting time increases with lower permitted speeds of lines as trains need more time to reach the crossing station. Lower headway times enable rides within shorter time intervals. This is a useful precondition for service on-demand. Additional trains can follow another train shorter than with longer headway times. This results in less waiting times for travelers, while offering a demand-oriented service. Thereby, more than the expected traffic volume of up to 50 trains on each day on the single-track standard line R 80 can be realized.

Headway times of conventional trains vary between the scenarios. The longest headway time is seen in scenario II: reduced speed limits of the lines lead to longer headway times. Due to the speed reduction, the trains need more time for driving the same distance. Conventional trains have the shortest headway time in scenario IV. In this scenario, the fixed block sections are about 5 km long, which is only a quarter of the length of the other fixed block sections. However, the shortest headway time does not equal one quarter of the headway time of the other scenarios, which is due to the significant block section.

In summary, higher speed limits and short block sections lead to short headway times for conventional trains. However, driverless trains have to wait on single-track lines in crossing stations for trains from the opposite direction. The waiting time is similar to conventional trains. To make driverless driving more attractive, lines should be equipped with long fixed block sections and reduced speed. Single-track lines with long waiting times for crossing train movements in crossing stations affect driverless operations negatively as the results do not differ much from conventional trains. Therefore, distances between crossing stations should be as short as possible to make driverless operation more attractive.

Scenario V with changed entry delays has an impact on the practical capacity. For our example lines, the input variables for entry delays are set according to (DB Netz AG (2009)):

- Probability of an entry delay: 50 %.
- Mean entry delay: 2 min.

With this input, the practical capacity of railway lines for each direction can be calculated by applying the STRELE formula (see section 2.2). There is no information about entry delays given for driverless trains. Therefore, assumptions are necessary. As described above, operations with driverless trains could lead to less entry delays. Therefore, we assume that the mean entry delays decrease in one scenario by 10 % and in another scenario by 50 %. This leads to mean entry delays of 1.8 minutes and 1.0 minute. The results of the practical capacity calculation are listed in Table 5 showing the practical capacity for the direction from station A to station F on the double-track line. It is also possible to calculate the practical capacity for single-track lines. However, the results are similar to those of double-track lines and consider only the capacity for one direction, which does not represent operations on single-track lines.

Table 5: Practical capacity by changed mean entry delays from station A to station F on the double-track line (trains / 24h)

	Scenario I		**Scenario II**		**Scenario III**		**Scenario IV**	
	c. t.	**d. t.**	**c. t.**	**d. t.**	**c. t.**	**d. t.**	**c. t.**	**d. t.**
2min	54	553	50	553	54	553	111	553
1.8min	55	561	50	561	55	561	114	561
1.0min	58	630	53	630	58	630	129	630

c. t. = conventional trains | d. t. = driverless trains

Table 5 shows that the practical capacity varies largely between conventional and driverless trains. This difference results from the train control system and slightly other vehicle characteristics necessary for driverless operations. The practical capacity reflects the results of the headway times: large headway times have a negative impact on practical capacity. As seen in Table 4, headway times of driverless trains do not really change between the scenarios. The same is observed for the practical capacity in Table 5.

The practical capacity varies between the scenarios for conventional trains. Scenarios I and III lead to the same results because the last scenario has an impact on the speed of driverless trains. In scenario II, conventional trains reach the lowest capacity level. The headway time in this scenario is higher than in the basic scenario (see Table 4) and leads to a lower capacity. Shorter fixed block sections (scenario IV) strongly effect capacities. The capacity in scenario IV increases to more than the double of the basic capacity.

Table 5 does not contain the results of mixed operation because they are very similar to the results of operation with conventional trains. Mixed operation allows only a slightly larger practical capacity than conventional operation. The headway times of conventional trains especially affect capacity.

In general, less mean entry delays have a positive effect on practical capacity as more punctual operations lead to higher line capacities. Furthermore, velocities of lines and trains, and the length of fixed block sections have a positive effect on capacity. To make driverless driving more attractive, lines should be equipped with long fixed block sections and have reduced speed limits.

In summary, operational effects of driverless trains depend on many factors. Moving blocks are the basis for successful operations with those trains. They enable lower headway times for one direction, higher practical capacities and a service on-demand. However, due to their lower maximum speed, driverless trains have higher running times than conventional trains in most scenarios.

5 Conclusion and outlook

We have analyzed effects of driverless trains on two different lines by using different scenarios. It was assumed that driverless trains can drive in moving blocks, while conventional trains can only drive in fixed block sections. Due to vehicle characteristics and lower velocities of driverless trains, operations with those trains are actionable on lines with a low permitted speed, e.g. on secondary lines. Because of features on secondary lines and driving on sight, maximum speed of driverless trains is set on those lines at 70 km/h.

The analyses were made for running times, headway times and theoretical capacities for conventional and driverless trains. For some scenarios the results differ, but for other scenarios the results are equal as some changes are not affected by the usage of driverless or conventional trains. The results of mixed operation are comparable with an operation only with conventional trains. For the sake of completeness, we also analyzed an operation with moving blocks by conventional trains. The results for headway times and practical capacity are comparable with driverless trains.

Due to different factors, operational effects of driverless trains can be observed. In general, driverless trains could increase the attractivity of lines. For our calculations, moving blocks are the basis for successful operations with those trains. They enable

- low headway times and
- high practical capacities.

Furthermore, a service on-demand does not depend on train control system. Driverless trains can carry out demand-oriented service, e.g. during off-peak time, which is difficult to implement with conventional trains. This could lead to more attractive rail transport, in particular on secondary lines. Such lines often have capacity reserves for offering additional services. An operation without moving blocks is also possible. Then, driverless trains could replace conventional trains respectively drivers. But in that context, not all listed advantages of driverless operations can be implemented. An operation with fixed block sections is a disadvantage for on-demand services because trains would follow each other in long headway times, particularly due to the length of block sections. Driving in fixed block sections leads to long headway times. Table 6 summarizes the characteristics having positive effects on driverless operation on secondary lines.

Table 6: Positive effects on driverless operation on secondary lines

Characteristic	Positive effects on driverless operation
Running time	Less permitted speed of lines Less permitted speed of trains Long block sections
Headway time	Less permitted speed of lines Less permitted speed of lines Short distances between crossing station (single-track lines)
Theoretical capacity	Less permitted speed of lines Long block sections

In the future, further analyses are necessary to better evaluate driverless operations. The analyses should also consider other types of vehicles and other lines with different layouts, e.g. shorter distances between crossing stations and different velocities. Furthermore, an operation with different vehicles or changes of the used train control system are practicable. Subsequently, more detailed results of operational effects of driverless trains are possible.

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