Jörn Pachl

Railway Operating Technologies

Signalling · Timetabling · Capacity

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Preface

This textbook covers two subjects of railway science that, while often taught separately, are closely connected. One subject is the signalling and train control principles, and the other subject is timetabling and capacity. Appropriate design of signalling and control systems requires an understanding of their capacity effects. On the other hand, profound knowledge of the signalling and train control principles is needed to establish a conflict-free timetable and to evaluate the operational capacity.

After an introduction to the basic operational terms and definitions, the signalling principles for safe train control are covered in several chapters from an operational point of view. This is followed by a chapter on the modelling of train paths by calculating the running time and applying the blocking time theory to estimate the time slots that must be kept clear around the time-distance line for conflict-free train movements. Since the understanding of the signalling principles provided by the previous chapters is essential for the blocking time theory, and an accurate train path model is needed for the following chapters on timetabling and capacity, this chapter is the connecting link between these two knowledge areas. A final chapter explains how traffic control is organised to control train movements based on a given timetable. Here, the two subjects come together.

While this textbook is based on ideas from my earlier textbook 'Railway Operation and Control', which was published by VTD from 2004 in several editions, it follows a new approach with a different structure. The objective is to deliver knowledge with a long-term value. For this, it concentrates rather on principles than on specific solutions. It is based on more than 30 years of teaching experience at universities in Braunschweig, Berlin, Beijing, and Bangkok, and in higher vocational training programs for the railway industry.

Jörn Pachl

About the Author

Prof. Dr.-Ing. Jörn Pachl
Studied Transportation Systems Engineering at the Dresden 'Friedrich List' University of Transport and Communications. From 1989 to 1991 he was a researcher at that university followed by a management position in the infrastructure planning department of the Hamburg region of German Railways from 1991 to 1996. In 1993 he received a doctor's degree from Technische Universität Braunschweig. From 1996 until retirement in 2026, he was a professor at that university and head of the Institute of Railway Systems Engineering and Traffic Safety. He has also an adjunct professor's position at TU Berlin and visiting professor's positions at Beijing Jiaotong University and at Mahidol University in Bangkok. Prof. Pachl is author and co-author of several textbooks on railway operations and signalling.

1 Basic Elements and Terms

Rail transportation has specific characteristics by which it differs significantly from other transportation modes. The key elements relevant for understanding railway operations and signalling are described here. This textbook is based on generic terms and definitions that are introduced in this chapter. Since no international standard for railway-related terms exists, terms and definitions used by individual national railways may differ in some aspects from those used in this textbook.

1.1 Main Characteristics of Railway Systems

A railway system has two essential characteristics by which it differs from other transportation systems, particularly road traffic:

– A railway is a guided transportation system.
– There is low adhesion in a steel-on-steel system.

In a guided transportation system, movable track elements are needed at turnouts to set diverging routes. Also, conflicting movements must be locked out at grade intersections. Therefore, for the safe passage of a train through turnouts and crossings, a route must be set that locks all movable trackside elements in the proper position and locks out conflicting movements. This is accomplished by the interlocking system as one part of the signalling technology.

The low adhesion between the wheels and the rail has two consequences. First, it leads to low rolling resistance, which is the reason for the low energy consumption of rail transportation. Second, the low friction factor reduces the maximum braking force that can be transmitted between wheel and rail. The proportion of the weight that the braking force must not exceed to safely prevent the wheels from sliding along the rail is about 10%. This also means that the maximum braking deceleration is limited to about 10% of the acceleration due to gravity. This is about eight times less than in road traffic and leads to braking distances that significantly exceed the viewing range of the driver. Even for movements running at very low speeds, e.g. shunting movements, safe train separation cannot be accomplished by trains following each other by sight based on the viewing range of the driver. Instead, signalling technology must provide safe train separation through block systems in conjunction with lineside or cab signalling and Automatic Train Protection (ATP).

The braking distance of a train does not mainly depend on the weight of the train but on the percentage of the weight that is used to transmit braking force between wheel and rail. Trains with the same braking ratio generally have the same braking distance. For safe train separation, a train must always have a clear track ahead that is at least as long as the braking distance. Thus, from a capacity viewpoint, it makes sense to assemble vehicles into trains. All vehicles that form a train require just one common braking distance for the entire consist. This significantly reduces the capacity consumption produced by the long braking distances. This is why railway transportation is based on running trains instead of individually propelled vehicles.

1.2 Classification of Railway Systems

Railway systems may be classified by different criteria. A common approach is to distinguish between heavy and light rail systems (figure 1.1). Heavy rail systems are the standard railways and other railway systems that are based on similar technology. The standard railways form the nationwide railway system. Due to a high degree of standardisation, most railway vehicles may operate on the entire national rail network. However, the access of locomotives to specific lines may be restricted due to axle loads or requirements for specific equipment. There are also dedicated lines for a specific kind of traffic (e.g. high-speed lines) where other kinds of traffic are excluded. Most standard railways offer transportation services to customers on the public transportation market.

Heavy rail transit railways are metro systems that offer public transportation in densely populated urban areas. Most metro lines run either underground or on elevated tracks to avoid conflicts with road traffic. While the technology is similar to the national standard railway system, some standards may differ. Therefore, the heavy rail transit networks are usually kept separated from the standard railway network.

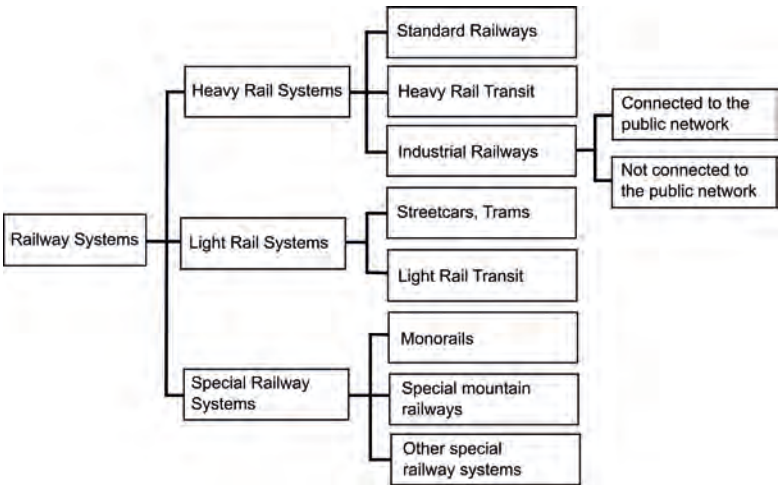

Figure 1.1: Classification of railway systems

Besides these public railways, industrial railways exist in many industries. Most industrial railways are connected to the public network. These railways are used to provide industrial facilities access to the public network but also for internal rail traffic within an industrial or port area. Industrial railways not connected to the public network can mainly be found in mining industries. Some mining companies deliver their mining products (mainly coal and ore) with their own trains on their own tracks to power plants, ports, and other destinations without using the public network.

Light rail systems are passenger railways used for city transit or regional passenger traffic. Vehicle and track design is mostly much lighter than on standard railways. Traditional streetcars (trams) share their right of way with road users. On more advanced light rail systems, often called light rail transit, the shared use is limited to intersections and some areas with limited space, so that most lines are kept separated from road traffic. A nationwide

standardisation of light rail systems is not required since the different networks are separated from each other. Special rail systems are a third general category to cover all railways that meet neither the characteristics of heavy rail nor the characteristics of light rail systems.

This textbook concentrates on the principles of heavy rail systems. Traditional streetcar systems are not covered. However, many principles may also be applied to light rail transit systems on sections separated from road traffic.

1.3 Key Operating Tools

In contrast to most other transportation systems, railway traffic is controlled from the infrastructure side. Trains cannot freely move through the network and make their own decisions about which route to take. Instead, trains are guided on a path predefined in the timetable on which safety is guaranteed by infrastructure control systems. This requires an interaction between three subsystems that may be seen as the key operating tools for rail traffic control:

– interlocking and operation control systems
– signals
– timetables

The task of the interlocking system is to set a safe route for a train movement. A safe route means that the track section is clear, all movable track elements are locked in the proper position, and the train is protected against conflicting movements. Route setting for an approaching train is initiated from an operation control system either by manual action on a user interface or by an Automatic Route Setting system (ARS) that uses the timetable data for automatic route setting.

When a route has been set, a movement authority, i.e. the right to occupy the track section that is protected by the route, has to be transmitted to the train. This is the purpose of signals. Signals are a one-way communication system by which trains are guided from the infrastructure side. There are two basic types of signals:

– lineside signals
– cab signals

While lineside signals are the traditional form of signalling, they are still the dominating form of train control and even used in many new installations. A lineside signal indicates to the driver whether the train has authority to proceed into the next section. Therefore, by lineside signals, movement authorities can only be transmitted at discrete points. Cab signals indicate the guiding information directly on the driver's desk. For this, a continuous data transmission system from track to train is needed. Cab signalling is generally required on high-speed lines, and on most railways on all lines where the speed exceeds 100 km/h. When running at high-speed, the time window to safely read the aspect of a lineside signal would be too short. Besides enabling the control of high-speed trains, cab signals will also improve capacity since the movement authority can be continuously updated. That is why, with the availability of digital radio systems that can be used for continuous data transmission, lineside signals on conventional lines are also increasingly being replaced by cab signals.

The timetable is not just a planning tool but contains a predefined path for each train from which the control data for guiding the train is derived. While the timetables used in control centres contain the relevant data for all trains running through the control district, the driver's timetable contains the data needed to safely drive the train on the entire train run. The driver's

The right column of the sheet contains the elements that are locked by operating the elements in the left column. If a point number is in brackets, these points will be locked in reverse position. If a row contains a point number both in normal and reverse position, the points will be locked in any position. These are facing points where different routes split. The middle column contains the conditions for conditional locking. The elements of the right column will only be locked if these conditions are in effect. Conditional locking is required to lock points and opposing signals depending on the position of the facing points. For permanent locking, the field in the middle column is left blank.

3.2.2 Route-based Interlocking

Route-based interlocking appeared with the first mechanical lever frame systems developed in Germany. Completely different from the British cascade logic, it led to a significant simplification of the mechanical locking frames. When setting a route, points can be moved in any sequence. When all points are in the proper position, a route lever is pulled. The route lever locks all points of the route and releases the signal lever. In electro-mechanical systems (power frames), the route lever will directly clear the signal. Route-based interlocking was adopted by all railways that have their roots in the German system. With the emergence of relay interlockings, many railways that used the cascade logic in their mechanical systems switched to a route-based logic in relay technology.

In route-based interlocking, the interlocking is completely based on predefined routes that are described by a route control table. In that table, the rows represent the routes and the columns represent the interlocking conditions relevant for these routes. Table 3.2 demonstrates the principle for the small junction of figure 3.14. In this example, the table sheet just contains route conflicts and point positions. A full route control table may have more columns for track clear detection, route locking and release criteria, and signal aspect sequences. Some railways establish separate tables for these issues, however.

The contents of the route control table may be directly transformed into the software of a computer-based interlocking or into the wiring diagram of a relay interlocking. The internal logic of relay interlockings following this principle is also called ‘free-wired’ logic because every interlocking has its own specific wiring according to the control table. The shortcomings of route-based interlocking are that the route control tables may become very complex for larger layouts. In relay interlockings, the manual design of the relay circuitry based on the route control table may also become a very complex task. However, route-based interlocking is still a suitable principle for the design of interlocking systems for layouts of moderate complexity. It is also used in several computer-based interlocking systems.

Route	Routes locked out	Points	
		normal	reverse
11-B1	11-B2, 11-C, 21-B1, 12-A1, 12-A2, 22-A1, 32-A1	1, 2, 3, 4	
11-B2	11-B1, 11-C, 21-B1, 21-B2, 21-C, 12-A1, 12-A2, 22-A1, 22-A2, 32-A1, 32-A2	1, 2, 5	3, 4
11-C	11-B1, 11-B2, 21-B1, 21-B2, 21-C, 12-A1, 12-A2, 22-A1, 22-A2, 32-A1, 32-A2	1, 2	3, 4, 5
21-B1	11-B1, 11-B2, 11-C, 21-B2, 21-C, 12-A1, 12-A2, 22-A1, 22-A2, 32-A1, 32-A2	3, 4	1, 2
21-B2	11-B2, 11-C, 21-B1, 21-C, 12-A2, 22-A1, 22-A2, 32-A1, 32-A2	1, 2, 3, 4, 5	
21-C	11-B2, 11-C, 21-B1, 21-B2, 12-A2, 22-A1, 22-A2, 32-A1, 32-A2	1, 2, 3, 4	5
12-A1	11-A1, 11-B2, 11-C, 21-B1, 12-A2, 22-A1, 32-A1	1, 2, 3, 4	
12-A2	11-B1, 11-B2, 11-C, 21-B1, 21-B2, 21-C, 12-A1, 22-A1, 22-A2, 32-A1, 32-A2	3, 4	1, 2
22-A1	11-B1, 11-B2, 11-C, 21-B1, 21-B2, 21-C, 12-A1, 12-A2, 22-A2, 32-A1, 32-A2	1, 2, 5	3, 4
22-A2	11-B2, 11-C, 21-B1, 21-B2, 21-C, 12-A2, 22-A1, 32-A1, 32-A2	1, 2, 3, 4, 5	
32-A1	11-B1, 11-B2, 11-C, 21-B1, 21-B2, 21-C, 12-A1, 12-A2, 22-A1, 22-A2, 32-A2	1, 2	3, 4, 5
32-A2	11-B2, 11-C, 21-B1, 21-B2, 21-C, 12-A2, 22-A1, 22-A2, 32-A1	1, 2, 3, 4	5

Table 3.2: Route control table for the layout of figure 3.14

3.2.3 Geographical Interlocking

Geographical interlocking was first developed for relay interlocking systems to reduce the effort for designing complex interlocking layouts in free-wired logic. In geographical relay interlockings, the track elements are represented by pre-fabricated relay groups, i.e. boxes containing all relays needed to control a particular element including the wiring. The relay groups have sockets by which they can be connected by multi-wire cables in accordance with the track layout. By connecting the relay groups, the correct circuitry for a given layout will automatically appear. For specific functionalities, special plugs could be attached to the relay groups to modify the internal wiring. That simplified the design of complex relay interlockings significantly. The signal planners were no longer required to manually design the electric circuitry. Instead, they established a diagram, in which the relay groups are represented by boxes that are connected by lines representing the multi-wire cables. For the special plugs to be attached to specific relay groups, the relevant plug IDs are entered into the boxes.

7.2.2 Recommended Area of Traffic Flow

From the waiting time curve, a recommended area of traffic flow can be derived. If the traffic flow was below that area, the operational quality would be excellent, but there would also be a lot of unused capacity. Above that area, the waiting times would slow down the traffic in an unacceptable way. That area has two limits:

– the minimum of the relative sensitivity of the waiting time
– the maximum of the traffic energy

The sensitivity of the waiting time equals the gradient of the waiting time curve (i.e. the 1st derivative of the waiting time curve). The relative sensitivity of the waiting time results from the sensitivity divided by the absolute amount of the waiting time:

$$SEN_{rel} = t_w'/t_w$$

SEN_{rel} Relative sensitivity of the waiting time

t_w Average waiting time per train

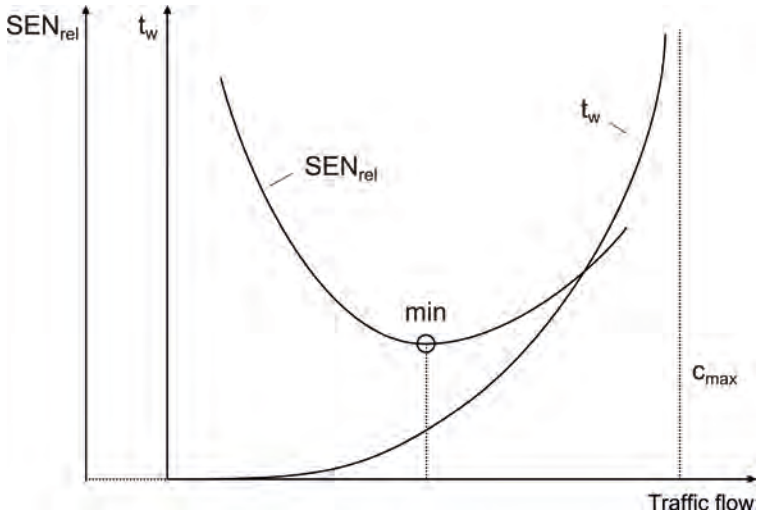

Figure 7.6: Relative sensitivity of the waiting time

The relative sensitivity of the waiting time has a global minimum (figure 7.6). Up to that point, an increasing flow of traffic only causes a very moderate increase in waiting time. If the line is operated at a traffic flow below this point the capacity of the infrastructure will not be well exploited.

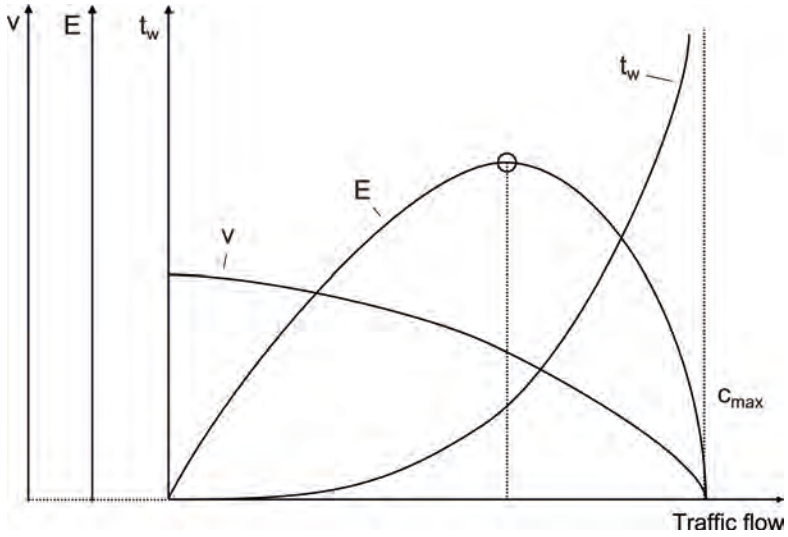

Figure 7.7: Traffic energy

The traffic energy is calculated from the traffic flow multiplied by the average speed. If the traffic flow increases, the average speed will decrease. At the point of maximum line capacity, the average speed is zero. There is an analogy to kinetic energy in physics. The traffic energy may be regarded as the moving 'mass' in the form of the trains that are in motion on the line at the same time (the traffic density) multiplied by the square of the speed. This can be transformed into the traffic flow multiplied by the speed:

$$E_{traffic} = n/s \cdot v^2 = n/t \cdot t/s \cdot v^2 = n/t \cdot v$$

$E_{traffic}$	Traffic energy
n	Number of trains
s	Length of the line
t	Time
v	Average speed

The traffic energy curve has a global maximum (figure 7.7). Above this point, an increasing traffic flow will cause an inadequate reduction of the average speed. Figure 7.8 shows both limits of the recommended area of operation in a combined diagram. To judge by practical experience, in passenger operations, the traffic flow should be close to the lower limit.

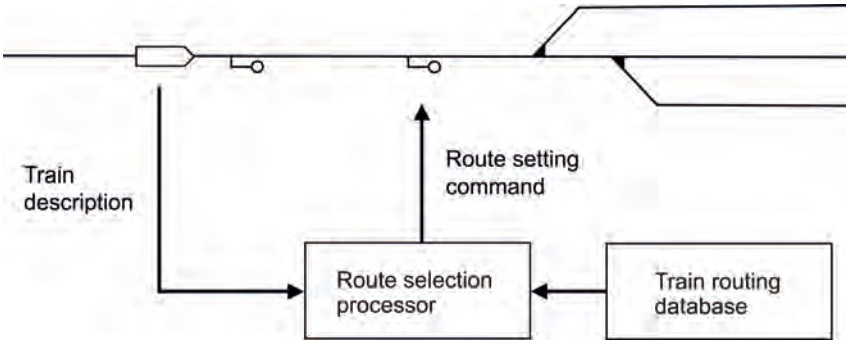

Figure 9.6: Route selection by train ID

Route selection by train ID is the general standard today. It is effected by a database that contains the routes for all train IDs. When a train is approaching a signal, a route selection processor will read the route for the train ID from that database (Figure 9.6).

In such an ARS system, there are two ways to handle train path conflicts in case of delays:

– timetable-based ARS
– destination-based ARS

In a timetable-based ARS system, all routes are set in compliance with the scheduled train sequence. When a train path conflict occurs, the time a train would wait for a delayed train that is scheduled ahead of its own train path depends on pre-defined waiting rules that can be set individually for each conflict point.

A timetable-based ARS system requires a database that contains the routes, the timetable data, and the waiting rules of all trains. Train path conflicts can only be solved by altering the timetable. To do this automatically, the ARS system has to be connected to a computer-based dispatching system that provides traffic management functions (see chapter 9.2.3). When a decision to change the train sequence has been made, the dispatching system would automatically create new timetable data for the ARS system. Without such an overlaying dispatching system, the ARS data may be manually edited by the dispatcher. However, from experience in practical operations, this is often too time consuming. So, if the dispatcher has decided to change the train sequence, the ARS is switched off to set routes manually. For this purpose, the ARS can be switched off for individual trains. So for all trains not inflicted by the conflict, route setting is still done automatically.

A destination-based ARS system sets routes automatically, regardless of the scheduled train sequence. The database that is used for route selection contains either the routes of all trains or a special destination code as a part of the train ID. In advanced destination-based ARS systems, conflicts are handled based on train priorities, to minimise delay for the superior trains.

When, in a destination-based ARS system, two trains are approaching conflicting routes without a sufficient time interval for passing the intersection, a decision must be made as to which train may pass first. For this purpose, the trains have to be detected by the ARS system before reaching the approach point for automatic route setting. This could be done by reserving a certain length of track ahead of the movement authority for every train. If, at an intersection, the reserved lengths of different trains do overlap each other, the train with higher priority will pass first (figure 9.7).

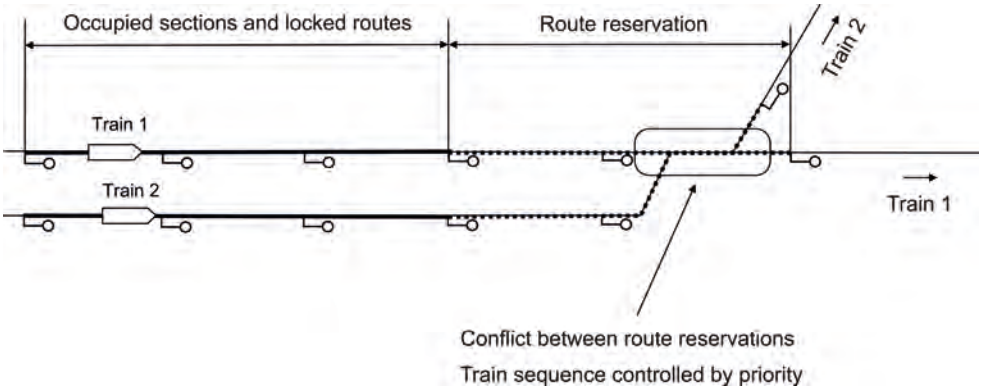

Figure 9.7: Train sequence controlled by priority of trains

However, as an automatic decision making just based on the priority of trains does not look at the whole picture, it may actually make the situation worse by causing new conflicts. To avoid this, the dispatcher has to supersede the priority decisions by manual route setting. In some ARS systems, the priority control can be switched off, so that at all conflict points, the ARS will apply a first-in-first-served logic as long as the dispatcher does not interfere by manual route setting. Besides critical situations, in which the priority control may cause new conflicts, it is sometimes also switched off in congested areas, since granting priority may have a negative impact on capacity.

Another form of conflict to be solved by an ARS system are deadlocks. A deadlock is a situation in which a number of trains cannot proceed at all because every train is blocked by another one (figure 9.8). The probability of such situations is particularly high in single-track operations with a series of successive passing tracks and a high density of traffic. But deadlocks may also occur in complex interlocking arrangements.

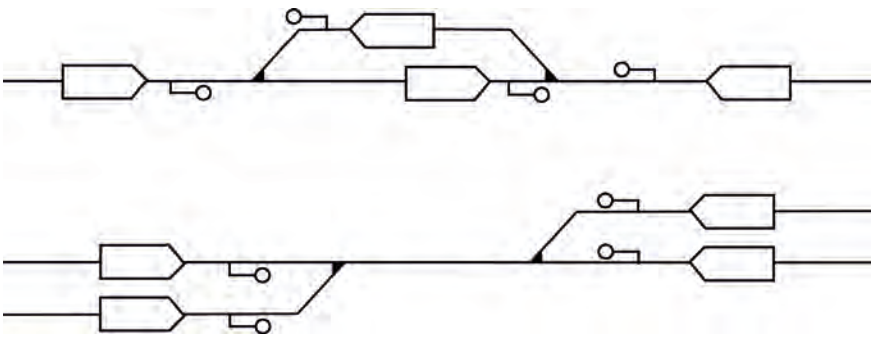

Figure 9.8: Simple deadlock examples

This textbook covers two closely connected subjects of railway science. One is the signalling principles, and the other is timetabling and capacity. Appropriate design of signalling systems requires an understanding of their capacity effects, while profound knowledge of the signalling principles is needed to establish a conflict-free timetable and to evaluate the operational capacity. The connecting link between these two knowledge areas is a chapter on train path modelling. While train path modelling requires an understanding of the signalling principles, it is the basis for timetabling and capacity.

The contents include:

- Block systems
- Interlocking principles
- Automatic train protection
- Level crossings
- Modelling train movements
- Capacity
- Timetabling
- Traffic control

The knowledge provided in this textbook is based on more than 30 years of teaching experience at universities in Braunschweig, Berlin, Beijing, and Bangkok, and in higher vocational training programs for the railway industry.

Target groups are:

- Students and early career professionals in the rail sector
- Researchers and teachers in railway programs at academic institutions
- Consultants working in railway signalling and operations
- Software developers for rail traffic control and planning applications

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