Capacity benefits of dynamic route assignment in nodes – a qualitative analysis

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Capacity benefits of dynamic route assignment in nodes – a qualitative analysis

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Abstract
In many densely populated areas, capacity increases in the railway network are necessary. However, space for additional tracks is limited. Therefore, increasing capacity of the existing network is a major goal of railway companies and politics. The railway control, command, and signalling (CCS) technology has an important impact on capacity. One of the major functions of the CCS is the assignment of track infrastructure to trains in nodes (route assignment). To maintain safety, the interlocking system blocks the assigned infrastructure so that it cannot be used by other trains. In order to maximise capacity, the safety-related minimum duration as well as the minimum spatial extension of the assignment should be as small as possible. Today, the interlocking systems usually use predefined, fixed train routes. As a result, often more track infrastructure is assigned to a train than necessary for a longer duration than required. For a long time, the preconditions for dynamic route assignment such as a precise localisation and a continuous communication between trackside CCS and the trains were not given. Emerging CCS technologies change this circumstance, so it seems reasonable to examine how an interlocking system that supports dynamic route assignment could contribute to the goal of increasing capacity. For this purpose, the article identifies requirements for the operating principles of such an interlocking and illustrates the capacity benefits of the dynamic route assignment approach with the aid of specific operational scenarios.

Keywords
qualitative capacity analysis; route assignment; train route; interlocking system, ETCS

1 Introduction

Due to predicted growth in passenger numbers and freight volume, increases in the capacity of the railway system are necessary. However, building new tracks is time-consuming and costly, and the interests of local residents must be taken into account. Therefore, considerations should be given to how capacity can be increased on the existing network. Next to the pure running time, the control, command and signalling (CCS) technology has an important impact on capacity (Goverde et al (2013); Oetting and Griese (2016)). It influences both the occupancy times as well as the stability of operations and thus the amount of buffer times to be included in the timetable.

By issuing a movement authority, the CCS technology assigns a part of the track infrastructure as protected train route for the train's exclusive use to ensure a safe passage, especially through nodes. In order to avoid accidents, the assigned route must be free of other trains and must not intersect with train routes of other trains. In order to enable using the track infrastructure in a capacity-optimal way, the route assignment should be as small as possible in terms of its spatial (extension of the assigned infrastructure) and temporal (duration of the assignment, which corresponds to the occupancy time) extent without restricting the train's journey.

Today, the CCS mostly uses fixed spatial sections of the track infrastructure (fixed train routes) for route assignment in nodes, which were predefined during the planning of the interlocking system (Pachl (2020); Theeg and Vlasenko (2020), Maschek (2018)). As an alternative, a dynamic route assignment is conceivable, which assigns sections of flexible length to the train and allows changing the extent of the route assignment continuously depending on the need of the train at each point in time. Ideally, the sections could end at any location of the track infrastructure, depending on the current operational situation (e.g. the needs of other trains in the area). To realise such a dynamic route assignment with a high capacity, the following preconditions are necessary:

- an interlocking system that supports to assign routes to any location of the track network, ensures their safety with a generic interlocking logic (cf. e.g. Menzel (2019)), and is able to dynamically transmit assignments of a flexible length
- an Automatic Train Control (ATC) system that can process a movement authority with a flexible length and is able to display it to the train driver (cab signalling)
- a precise localisation technology so that the train driver can closely approach the end of the movement authority without having to rely on optical signals that mark the stopping location
- a continuous and safe communication technology that allows transmitting a new movement authority to the train at any location and time

The second and fourth precondition could be realised e.g. with the European Rail Traffic Management Systems (ERMTS) (see chapter 3). Regarding the third precondition, we assume that a sufficiently accurate localisation technology exists at least in the area of the nodes. This article focuses on the first precondition. The aim is to analyse the potential of an interlocking system that supports dynamic route assignment to achieve the goal of increasing capacity as well as to raise stability of operations and reduce delays. For this purpose, the article identifies requirements for the operating principles of such an interlocking and illustrates the capacity benefits of the dynamic route assignment approach with the aid of specific operational scenarios.

2 Potential influence of the route assignment on capacity

With regard to the objective of achieving an increase in capacity, the potential influence of the route assignment on capacity should first be considered in more detail. According to UIC Code 406 (International Union of Railways (2013)), the capacity consumption of a train that uses a track section is relative to the sum of its occupancy time and additional times, of which the latter represents "any time value added to secure quality of operation (buffer time, quality time, etc.)" (ibid., p. 13). The occupancy time of a single train reflects how long a train occupies a track section for safety reasons. In the case of classical block sections, the occupancy time for one section consists of the elements shown in Figure 1.

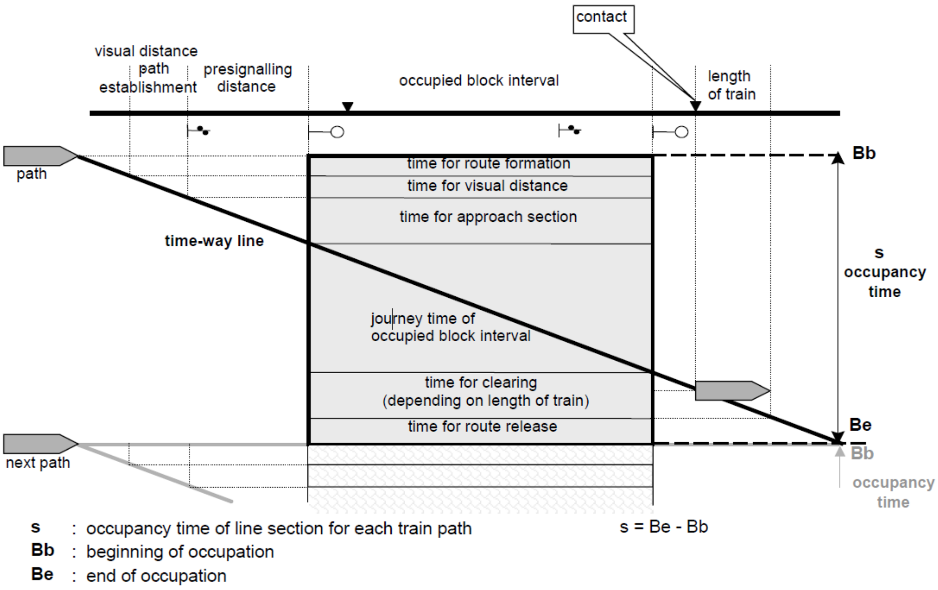

Figure 1: Elements of the occupancy times of a single train in case of block sections (Source: (International Union of Railways (2013))

If the trains receive the signalling information via cab signalling as listed in chapter 1 as a precondition for dynamic route assignment, the time for visual distance can be replaced by a driver perception time. Furthermore, in the case of cab signalling, the route formation and route release times consist of a variety of different communication times and processing times of the different technical systems involved in the process. (For more details about components of the occupancy time in combination with ETCS level 2 and 3 compare e.g. Büker et al (2019)).

In nodes, the occupied sections correspond to the train routes. In addition to the running path of the train, the route often contains a safety buffer behind the stop signal called distance to danger location/point or overlap. The overlap allows the train to approach with a higher speed because it still has a protected part of the track if it passes the stop signal. A longer overlap can allow for a faster approach speed and thus a faster release of previous sections that the train has already passed. Especially in nodes, this could enable allowing other trains to use previously occupied infrastructure elements earlier.

The length of a section, respectively in stations the length of the route, can influence the capacity because shorter sections decrease the trains' journey time for each section and thus, depending on the train sequence, also the time during which a train can follow a preceding train. Modern interlocking systems can already release parts of the routes separately if they get a safe information that the train has passed the subroute with its complete length (sectional route release). Each subroute and the overlap have their own occupancy time (cf. Figure 2). In current interlocking systems, the complete route needs to be blocked at once. Being able to block subroutes separately could be a potential for increasing capacity (hatched area in Figure 2). The same applies to a dynamic release of the overlap based on reliable real-time information about the train's position and speed, which determine the required length of the overlap. The possibility of assigning movement authorities for routes with flexible length would support the realisation of both potentials.

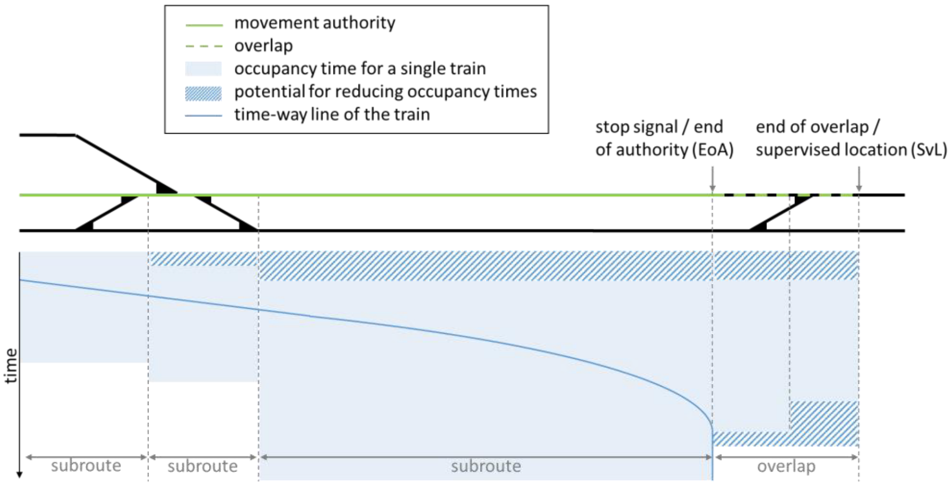

Figure 2: Occupancy times for a route with subroutes and overlap

A dynamic route assignment could also have an influence on the additional times because they contain components to reflect delays. If a dynamic route assignment would contribute to decreasing delays (especially reactionary delays) and thus more stable operations, necessary buffer times could be reduced in the medium term.

3 Framework conditions set by the ATC system

As stated in the introduction, a modern ATC system is an important precondition for the realisation of a dynamic route assignment. It has to be able to support cab signalling, continuous communication between the trackside CCS and the trains as well as movement authorities with a flexible length that theoretically can end at any point of the network. Since there are already existing systems that fulfil the requirements such as the European Train Control System (ETCS), their operating principles define the framework for optimising the interlocking system in order to enable dynamic route assignment. Therefore, it is necessary to understand the most important operating principles of such an ATC system. These operating principles are explained in this chapter by using the example of ETCS. For further details to ETCS please refer to (European Union Agency of Railways and ERTMS Users Group (2016); European Union of Railways (2020); Stanley (2011)).

ETCS supports cab signalling and allows for a continuous communication between the trackside CCS and the trains within its deployment levels 2 and 3. ETCS level 3 supports on-board train integrity monitoring as well, which is not required but advantageous for dynamic route assignment because it allows releasing parts of the route more continuously and at any location of the track network.

The trackside CCS generates the ETCS Movement Authority (MA), which allows the train to proceed according to the transmitted parameters for a specified distance (for which the interlocking system can guarantee the absence of other trains) in relation to a reference location. The ETCS on-board unit guarantees that the train can safely stop within its movement authority at all times to avoid a collision with a previous train. It is always possible to extend the MA as soon as an additional part of the track ahead is cleared. However, except in case of emergency, it is only possible to shorten a MA if the train confirms that it is able to stop safely in front of the new, nearer stopping location. Table 1 contains the most important parameters of the ETCS MA.

Table 1: Important parameters of the ETCS MA

Parameter	Description
End of authority (EoA)	The ETCS on-board unit calculates the service brake deceleration curve (SBD), which is decisive for the permitted speed, towards the EoA and supervises that the trains do not exceed the permitted speed. To calculate the permitted speed curve, ETCS adds time supplements to the SBD to include human and technical reaction times. The slope of the SBD depends on the braking capability of the train during normal operation.
Overlap and Danger Point	Localisation inaccuracies and imperfect braking behaviour make it difficult for the train to stay below the SBD at all times. To avoid unnecessary restrictive SBDs in order to maintain safety, it is possible to transmit an overlap or a static danger point. The difference is that the overlap can be released after a specified time has elapsed, which starts when the train is passing a specified location on the track. At the end of the overlap or, if not available, at the danger point is the Supervised Location (SvL). The ETCS on-board unit calculates the emergency brake deceleration curve (EBD) towards the SvL. The EBD has a higher safety margin than the SBD so that ETCS can guarantee that the train stops in front of the SvL with a sufficient level of safety.
Static Speed Profile (SSP)	The SSP contains the speed limit in flexible sections.

In order to maximise capacity with a dynamic route assignment, it is important to understand how EoA and SvL could be used to specify the end of the assigned route efficiently. EoA and SvL could be principally placed at any location on the track. It is possible to place them separately or both at the same location.

A separate placement could for example be beneficial if a scheduled stopping location is in front of the currently relevant danger point that determines the location of the SvL, and the interlocking system plans to reassign the track between the scheduled stopping location and the SvL to another train as soon as the first train does not need it anymore. Furthermore, in some countries it is possible to use the same overlap for two different trains because the chance that both trains pass the EoA is considered small.

In case EoA and SvL are at the same location, the permitted speed curve will depend on the more restrictive EBD curve that runs towards the SvL. The SvL has to be located in front of the currently relevant danger point. However, the latter case could still be beneficial because it allows to shift the permitted speed curve as far towards the currently relevant danger point as possible (cf. Figure 3). In the upper scenario of Figure 3, the permitted speed curve is steeper but the train must still start braking earlier, which could have a negative impact on capacity (cf. chapter 2).

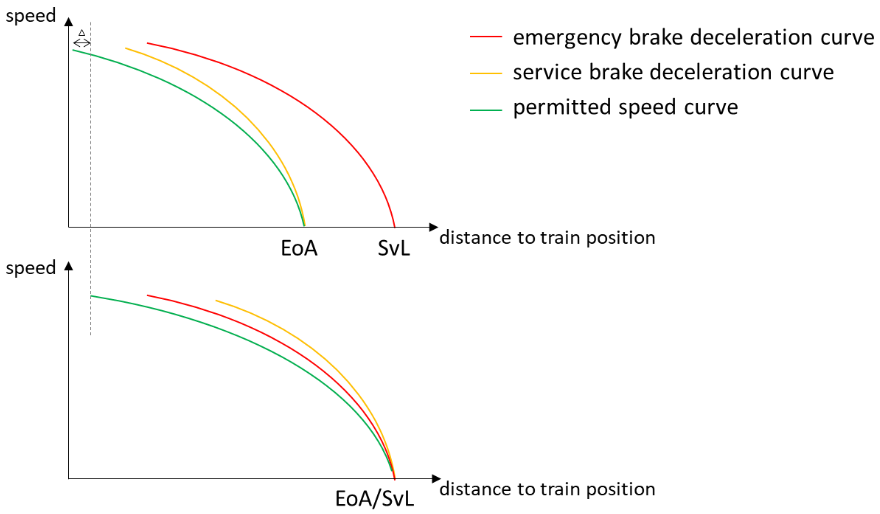

Figure 3: Simplified illustration of ETCS braking curves in case of separate locations for EoA and SvL (upper part) and the same location (lower part)
(cf. European Union Agency of Railways (2018))

4 Method

To determine the requirements for the operating principles of an interlocking system that supports dynamic route assignment and to identify the potentials of such an interlocking system regarding the increase of capacity, an appropriate methodical approach is required. It is possible to follow a systematic approach or an approach based on collecting qualitative data by including experts and practitioners. The systematic approach allows developing a capacity-optimal interlocking system that supports dynamic route assignment from scratch, which limits the risk of organisational blindness. However, including experts and practitioners increases the chance that the solutions provide a significant contribution to actual practical problems. Both methods have their advantages, so that it makes sense to combine them.

Together with experts from railway infrastructure managers, the following criteria for the solution were defined:

- priority 1: the required level of safety must be guaranteed
- priority 2: capacity shall be maximised
- priority 3: life-cycle cost of the interlocking system shall be as low as possible and consequently the planning and certification times of new installations of the interlocking system shall be minimised

The third priority reflects that, in practice, infrastructure managers often do not realise capacity-oriented changes to infrastructure or interlocking systems because the costs are too high. An important cost driver is costly and complex planning and certification processes. Furthermore, a complex roll-out could reduce the benefit of a new interlocking system because new units of the system cannot be installed frequently.

Starting point for the systematic approach must be the safety conditions that the route assignment must cover because they have the highest priority. The safety conditions can be deduced from the basic safety functions for railway operations. The other limiting factor is the framework conditions that were described in chapter 3. Based on the safety and framework conditions, the minimum requirements for the extension and duration of the route assignment can be defined. To optimise capacity, the interlocking system would ideally not necessitate expanding the extension or duration of the route assignment any further than the minimum requirements. Therefore, any other impact on the extension or duration of the route assignment should be assessed for its need in context of the framework conditions.

To get a complete picture of the impacts on the extension and duration of the route assignments and to align the operating principles of the interlocking system with the needs of the practice, two different methods were used. An observation and interview of dispatchers in a regional operations centre in Germany took place. This experience allowed adding the view of the operators on shortcomings and possible improvements of the current interlocking systems.

To get a more comprehensive impression of these topics, different experts were additionally involved, who could provide a greater overview of operational situations that occur on different topologies. The format of a workshop was chosen over the format of several individual interviews in order to allow the participants to inspire each other. Experts from several departments of the Deutsche Bahn who have leading roles in operations and safety systems took part in the workshop. The workshop included a brainstorming and a discussion of operational scenarios visualised on the fictive railway network of the railway operations training centre Darmstadt. The experts identified several operational scenarios, in which the most modern generation of interlocking systems in Germany acts suboptimal in terms of capacity. On this basis, further requirements for the operating principles of the new interlocking system can be defined.

5 Systematic approach

The systematic approach to deducing requirements for the operating principles of an interlocking system that supports dynamic route assignment follows the method defined in chapter 4 and uses the basic safety functions for railway operations as starting point. These are (cf. e.g. Maschek (2018), Menzel (2019))

- protection from collisions with other railway vehicles from the front (head-on collision), the back (rear-end collision) or from the side (flank collision),
- protection from derailment by exceeding the permitted speed or moving over a set of points that is not locked in the right end position,
- protection from entering unprotected hazard zones such as unprotected level crossings, end of track etc.

5.1 Extension of the route assignment

Based on the basic safety functions, the safety-related minimum requirements for the extension of the route assignment can be defined. The interlocking system uses the protected train routes mainly to avoid collisions by controlling the exclusive assignment of parts of the track infrastructure. Furthermore, the interlocking system could use the train route to specify the points that must be locked to avoid derailments. To fulfil these goals, the train route must cover at least the current track occupation of the train including safety margins in case of imprecise localisation and the part of the track whose occupancy cannot be avoided. The latter part refers to the braking distance plus a safety buffer (overlap) as compensation for imperfect braking behaviour.

Furthermore, the route should contain the flank collision hazard areas to avoid flank collisions. If all railway vehicles in the relevant area are in mode “Full Supervision”, no further flank protection measures are required. The risk of a flank collision depends on the probability that an unknown vehicle is in the network and on how likely such a vehicle could reach the flank collision hazard area. To follow the dynamic route assignment approach, a dynamic flank protection assessment based on the actual, real-time flank protection risk appears to be reasonable.

Figure 4 shows the safety-related minimum components of the spatial extension of the train route.

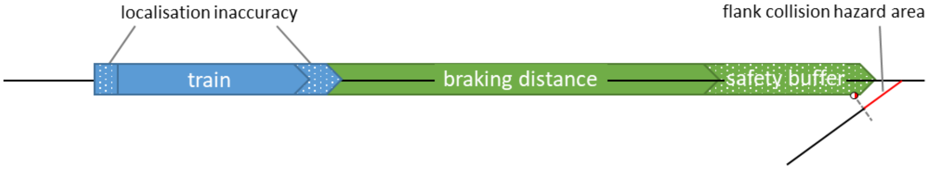

Figure 4: Safety-related spatial minimum components of the train route

The components in Figure 4 represent only the safety-related minimum requirements for the spatial extension of the train route. If the assigned route would have that extension, the train would have to start braking immediately to stay inside of its route assignment. For operational reasons, the route assignment should be longer. Therefore, it is necessary to define the safety-related maximum length as well. According to the basic safety functions, the extension of the assignable route is limited by route assignments of other trains (except some special cases in which safety buffers might be shared by different trains), unprotected hazard zones or unlocked points.

5.2 Duration of the route assignment

The elements of the occupancy time, as they were illustrated in chapter 2, define the safety-related minimum duration of the route assignment. For the case of dynamic route assignment, the considerations related to the occupancy time should not refer to an entire section, but only to a specific spot on the track network because the interlocking system can principally extend or shorten the train route to any point on the track.

A spot of the track must be assigned to a train at least as long as it is part of an active dynamic train route. Since the interlocking system has to assign a spot to a dynamic train route before the train route is transmitted to the train, there are no safety requirements as to when the assignment should start (the safety requirements define the minimum extension of the route assignment for the case the train gets a MA but not when it should get the MA). Therefore, operational considerations can determine the optimal moment to assign track infrastructure to a train. An exception applies when a new vehicle appears on the network. In this case, the interlocking system must assign the area that the vehicle covers, immediately.

The earliest release time depends on the moment when the interlocking gets to know that the spot is not covered by any of the safety-critical components of the train route anymore (cf. Figure 4). It is possible to release parts of the route both in front of the current position of the train as well as behind it. To release a spot in front of the current position of the train, the train must confirm that it will not reach it anymore with a sufficient level of safety. In case of ETCS, the train can use the message “Request to shorten a MA is granted” to send this information (cf. chapter 3). To release a part of the route assignment behind the current position of the train as flexible as possible, the interlocking system should be able to evaluate both, punctual trackside train detection systems and continuous train detection systems that contain train integrity monitoring. As for flank protection measurement, the duration of the assignment consequently depends on the duration of the assignment of the related flank protection hazard area.

From a perspective of safety, there are no requirements for the maximum duration of the route assignment (apart from some special cases such as maximum closing times for level crossings). However, from a capacity point of view, it makes sense to release infrastructure that the train does not need anymore, as early as possible to be able to reassign it to another train.

6 Identified potential for improvement from the insight into practice

As discussed in chapter 4, an insight into practice complements the results of the systematic approach to ensure the practical relevance of the operating principles of an interlocking system with dynamic route assignment and to identify potential capacity benefits. In the workshop with experts and during the observation of practitioners, the following potential for improvement was identified.

- The length of the overlap does not correspond to the braking capability of the approaching train so that either the interlocking system assigns more infrastructure than necessary to the train or trains must approach with a lower speed than possible. Although ETCS can calculate the braking curves according to the braking performance of the train, conventional interlocking systems can only assign overlaps with lengths that were planned before the installation of the interlocking.
- The moment of releasing the infrastructure elements of the overlap does usually not correspond to the moment at which the train ceases to need the overlap because it has stopped or it is slow enough to stop safely in front of the elements of the overlap.
- Flank protection measures prevent parallel train routes or limit overlap lengths, especially in case of delays or malfunctions of system components.
- In some countries like Germany, lengthy, often manual procedures in degraded modes of operation increase delays dramatically because many malfunctions of the system cannot be handled by the interlocking system itself. This point is not directly related to dynamic route assignment. However, dynamic route assignment could enable using more train routes and additional overlap lengths, which bypass the malfunction.
- In case of malfunctions, the usage of the infrastructure is often more restricted than necessary because the interlocking system cannot isolate the failure.

7 Requirements for the operating principles of an interlocking system with dynamic route assignment

According to the parameters that influence the length of the route assignment, the assumptions about the system environment and the identified potential for improvement, the following requirements for the operating principles of the interlocking system with dynamic route assignment were defined:

- Every location on the track infrastructure is a potential stopping location (EoA or SvL) to make MAs just as long as needed.
- At each moment while the train is approaching and for each individual train characteristic, the overlap is only as long as needed. This implies that it is possible to shorten the overlap when the train is slow enough and confirms that it does not need the additional overlap length anymore. The shortening is possible with the ETCS message “request to shorten a MA”.
- The interlocking system can automatically modify existing MAs in agreement with the train (ETCS message “request to shorten a MA”), e.g. in case of unexpected disturbances on the infrastructure in order to limit manual fallback levels and to be able to reassign the released infrastructure as soon as possible.
- The decision whether the interlocking system grants a requested route assignment depends on the current risk of a hazard instead of a fixed list of requirements in order to limit unnecessary blockings of infrastructure elements. The risk of a hazard must be lower than the required safety level (e.g. safety integrity level 4 according to EN 50129). To calculate the current risk of a hazard, the interlocking system could use all information about the current operational situation that are available and have the required level of accuracy. An example of such a piece of information would be how likely it is that a track area is occupied. E.g., the probability for an occupation is acceptably low if a train that safely monitors its integrity has passed the track area recently, but it is also acceptably low if a trackside detection system safely monitors that the train has completely passed the track area or that the track area is free of any vehicles.
- The interlocking system calculates the risk of a flank collision dynamically and locks flank protection devices only if it is necessary.
- Where possible, rules for degraded modes of operation are integrated in the interlocking system to avoid timely manual fallback levels in order to decrease delays and allow assigning as much infrastructure as possible.
- The logic works on a basis of generic rules in order to keep the planning and certification process of a new installation of the interlocking system for a new control area simple and allow for an easy integration of updates of the track infrastructure (compare the priority 3 goals in chapter 4).

8 Illustration of the capacity benefits based on example situations

With the aid of specific operational situations, the following scenarios qualitatively illustrate the capacity benefits of an interlocking system with dynamic route assignment that works according to the operating principles described in the previous chapter. A quantitative analysis is not included in the example description because the quantitative impact of dynamic route assignment depends largely on the specific infrastructure, the characteristics of the participating vehicles, and the national ruleset in which the scenario takes place (cf. chapter 9).

Most of the situations were identified and discussed in the workshop with experts. The example topology belongs to a fictive railway station. The coloured lines represent the train routes that the interlocking system has approved. The description of each scenario compares the improved situation with dynamic route assignment with the current situation. The current situation refers to the latest generation of interlocking systems that are currently in use in Germany as a reference case. However, the reference case is described as generically as possible.

For the understanding of the scenarios, it is important to consider the generic approach of a simple rule-based interlocking system due to the priority 3 goals of decreasing life-cycle cost and reducing planning and certification times of new installations of the interlocking system (cf. chapter 4). Otherwise, some of the capacity benefits could be realised with additional infrastructure or additional planning effort as well.

In the scenarios, the term "overlap" is used independently from its meaning as an ETCS term (which refers to a part of the track route between EoA and SvL that is time-limitedly reserved for the train). Instead, it refers to any part of the infrastructure that is reserved for a train but is located behind (seen from the perspective of the approaching train) the stopping location towards which the train is approaching (cf. Figure 5).

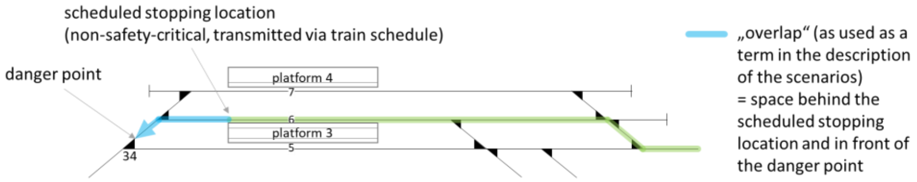

Figure 5: relevant terms used to explain the scenarios

Scenario 1

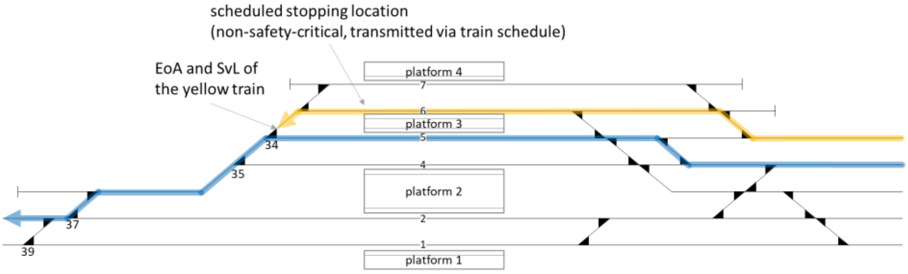

Figure 6: Scenario 1 – flexible overlap length to maximise the approaching speed

The first scenario illustrates the benefit of being able to set the ETCS EoA (end of authority) and SvL (end of the overlap) to any location on the track network in order to maximise the overlap and therewith the approaching speed of an approaching train. The scenario depicts the movement of two trains through the station. The blue train is going to pass through the station on track 5 without a stop. At the same time, the yellow train is approaching the station through a neighbouring track (track 6) and is going to stop at the end of platform 3 at the scheduled stopping location according to the train schedule (cf. Figure 6).

The approaching speed of the yellow train depends on the length of the available track behind the scheduled stopping location. The longer the available track, the faster the train can approach. Ideally, the SvL could be set in front of the relevant danger point, which is the clearance marker of the set of points that is required for another train. Depending on the route of the other train, this could be point 39, 37, 35 and 34. In Figure 6, it is point 34.

With the current electronic interlocking technology, the planner must plan reasonable locations for the EoA (usually where in case of optical signals, the main signals would be located) as well as overlaps prior to the installation of the interlocking system. To maximise capacity, in case of the example, four different overlaps would be necessary. Each of the four overlaps would end in front of one of the points mentioned above. Each overlap would allow a different approaching speed. For complex track layouts, a high number of projected overlaps increase the complexity of the interlocking system, which has negative impacts on the priority 3 goal of shortening the times for planning and especially certifying new interlocking system installations.

Furthermore, at least in the current praxis in Germany, the rule set for interlockings would not allow such a short overlap between the possible location of the EoA at the scheduled stopping location in track 6 and the clearance marker of point 34 (international rules are diverse). The reason is that the rulebook uses conservative uniform values to determine the minimum length of an overlap regardless of the specific train type and its braking capabilities.

In case of ETCS and an interlocking system with dynamic route assignment, both EoA and SvL could be placed at any location on the track without a specific planning of the possible stopping locations for the individual spatial instance of the interlocking system. Due to the flexible positioning of the EoA and SvL at any location on the track, the SvL could be located directly in front of the clearance marker of that set of points that is assigned to another train and thus represent an active danger point. According to the considerations in chapter 3, in this case it would make sense to place the EoA at the location of the SvL. This procedure would allow the fastest possible approach because all braking curves to be observed end at the furthest possible location from the scheduled stopping location.

Scenario 2

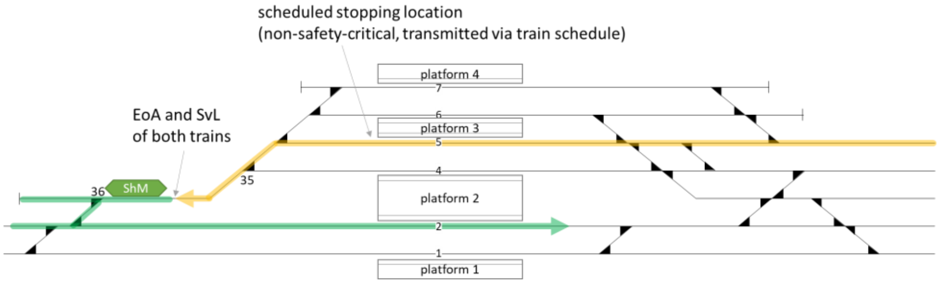

Figure 7: Scenario 2 – additional train routes to enable parallel movements

The second scenario illustrates how a dynamic route assignment could allow additional train routes. In this case, EoA and SvL are placed dynamically at the optimal location between point 35 and point 36 in order to allow the green shunting movement to leave the dead-end track while the yellow train can approach with the highest possible approaching speed. In the scenario, the yellow train is going to approach track 5 while a “shunting” movement (green line and object “ShM” in Figure 7) is set to leave a dead-end track towards track 2. Both movements (including the shunting movement) are equipped with ETCS and run in the highest operation mode of ETCS “Full Supervision (FS)”. This means, ETCS ensures that both movements will definitely stop in front of the transmitted SvL.

In existing interlocking systems, it would be necessary to plan an additional train route (or in some national systems shunting route) for the shunting movement until the mid of the track between the points 35 and 36 and an additional overlap for the yellow train to realise this scenario. However, it would not be possible to adjust the end of these train routes according to the length of the shunting movement in order to maximise the overlap of the yellow train and therewith its approaching speed.

In contrast to traditional interlocking systems, the new interlocking system can place the EoA and SvL at any spot on the track. Consequently, it is possible to place them between point 35 and 36 in such a way that the shunting movement can just pass over point 36 with its entire length and an acceptable speed (e.g. 25 km/h). The EoA and SvL of the yellow train could be placed at the same location because the ETCS braking curve calculation towards the SvL already contains a satisfying safety buffer. This optimal location of the SvL and EoA, which depends on the length of the shunting movement, limits the restrictions to the yellow train by maximising its overlap, so that it can approach its scheduled stopping location as fast as possible.

Scenario 3

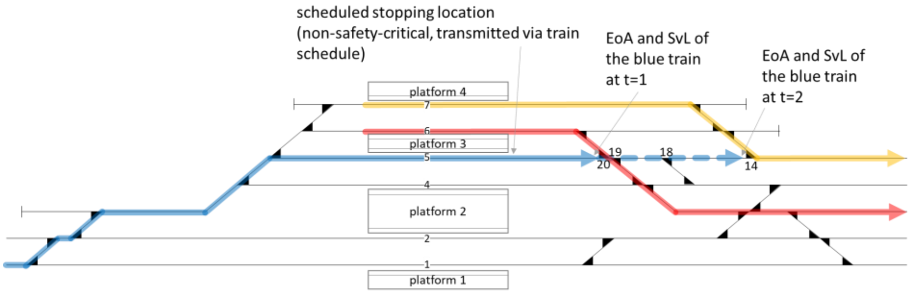

Figure 8: Scenario 3 – dynamic extension of short overlaps to increase the approaching speed after the MA has already been transmitted to the train

Scenario 3 focuses on the possibility to reassign infrastructure flexibly. Furthermore, it illustrates the possibility of very short overlaps. The scenario contains three trains (cf. Figure 8). The red and the yellow train shall leave the station while the blue train shall enter the station at the same time.

According to many national rules, in case of a conventional interlocking system, it is not possible for the blue train to enter the station because its overlap crosses the train route of the red train. Furthermore, it is not possible to establish a very small overlap between the scheduled stopping location and point 20 because of the required minimal length of an overlap as explained in the description of scenario 1.

In case of dynamic route assignment, the TMS could first set the EoA and SvL in front of point 20 because there is no restriction for the locations of the EoA and SvL. The train calculates its braking curves towards that location, even if the train consequently cannot reach the scheduled stopping location due to safety margins and localisation inaccuracies. As soon as the red train has passed point 20, which could be before the blue train has stopped, the interlocking system could allow expanding the MA for the blue train so that a faster approach of the blue train is possible. (The train could stop braking for a while because the ETCS on-board unit would shift the braking curves in the direction of travel.)

Scenario 4

Figure 9: Scenario 4 – flexible end of authority to prevent unnecessary stops

Scenario 4 illustrates how dynamic route assignment could prevent unnecessary stops. In the scenario, the yellow train shall leave the station and the blue train shall pass the station without a stop (cf. Figure 9). The yellow train has the higher priority and starts first. After it has passed point 37, the interlocking system could theoretically allow expanding the MA of the blue train.

With current interlocking systems, the blue train must stop at the fix location of the EoA of the train route that it uses to enter the station, which would most likely be somewhere in track 4. At this location, the blue train would have to wait until the yellow train has cleared the train route that the blue train is going to use to leave the station.

However, to avoid an unnecessary stop of the blue train, it would be optimal to maximise the length of its MA, which means setting the EoA of the blue train as far away from the train's current position as possible. The furthermost location that is still safe is at the clearance mark in front of the flank protection hazard area of point 37. In case of dynamic route assignment and trains that are in ETCS mode "Full Supervision", it is possible to set EoA and SvL to that location. The ETCS supervision guarantees that the train will stop in front of the clearance mark of point 37. In the best case, the yellow train would have passed point 37 already before the blue train reaches the clearance mark so that the interlocking system could allow expanding the MA for the blue train before the blue train has stopped.

Scenario 5

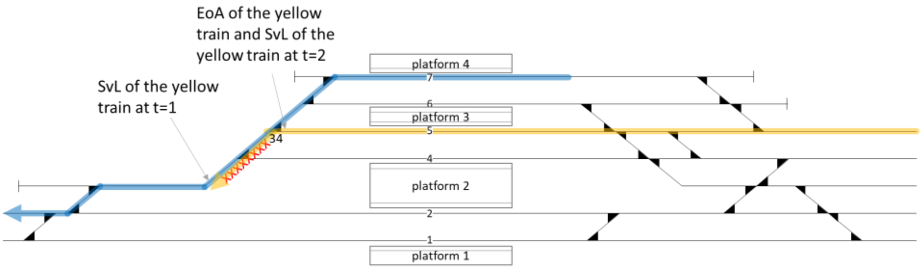

Figure 10: Scenario 5 – dynamic shortening of the overlap to enable other movements as soon as possible

Scenario 5 illustrates the benefit of being able to shorten the overlap dynamically as soon as it is not needed anymore to allow other trains to start or proceed their journey as soon as possible. In the scenario, the blue train shall leave track 7 but the yellow train is approaching track 5 at the same time (cf. Figure 10). Due to the high priority of the yellow train, it shall approach to its scheduled stopping location as fast as possible. Therefore, it initially gets a long overlap that occupies a part of the train route of the blue train behind point 34.

In case of conventional interlocking systems, the interlocking system would release the elements of the overlap after a fix time has elapsed. Instead, with the dynamic route assignment approach, the interlocking system could use the ETCS mechanism to shorten the MA in order to release the part of the track that the blue train request as soon as the yellow train does not need it anymore. This point in time would be reached when the yellow train is slow enough so that the distance between its scheduled stopping location and point 34 suffices as a safe overlap. Hence, the blue train could start its journey earlier.

Scenario 6

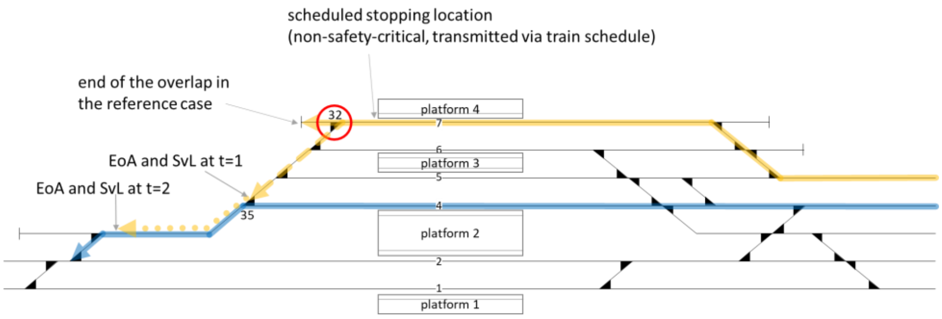

Figure 11: Scenario 6 – risk-based flank protection to maximise the approaching speed of another train

Scenario 6 illustrates a situation in which the dynamical risk calculation for the need of flank protection is beneficial in order to maximise the approaching speed of a train. In the scenario, the blue train passes the station on track 4 (cf. Figure 11). Therefore, in case of the conventional German rule set for interlocking systems, point 32 that leads to a short track, which could function as a parking position for locomotives, must be in the right position to provide flank protection for point 35. If the interlocking system would force point 32 in the right position, the overlap behind the scheduled stopping location of the yellow train would be quite small. As a result, the approaching speed of the yellow train would have to be low.

However, in many cases there is only a negligible risk of a flank collision from track 7, especially when the train on track 7 is in ETCS mode Full Supervision and the interlocking system knows that there is no uncontrolled vehicle between point 35 and the train on track 7. The fact that there is no physical flank protection for point 35 from trains on track 5 and 6 underlines that the flank protection function of point 32 is not essential. However, due to its flexible risk-based approach, the new interlocking system could shift the flank protection function from point 32 to the yellow train. Prerequisites are that the yellow train is fully supervised (e.g. ETCS mode “Full Supervision”) and the interlocking system knows that the track area between the current position of the yellow train and point 35 is free of other vehicles.

ETCS guarantees to stop the train before it reaches the SvL. The SvL could be placed directly in front of the potential flank collision hazard area at point 35. Due to the longer distance of the overlap between the scheduled stopping location of the yellow train in track 7 and point 35 than between the scheduled stopping location and the end of the short track behind point 32, the approaching speed of the yellow train could be higher. As soon as the blue train has passed point 35, the interlocking system could even extend the overlap of the yellow train further past point 35 to allow an even higher approaching speed.

If the occupancy status of track 7 is unknown, the interlocking system could still use point 32 as a flank protection device.

Scenario 7

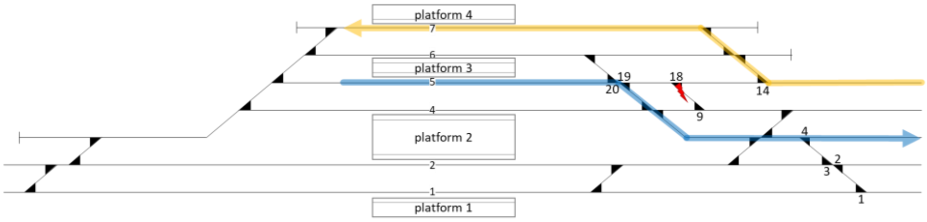

Figure 12: Scenario 7 – flexible flank protection measures to enable train movements in case of malfunctions

Scenario 7 illustrates how the interlocking system could avoid a (manual) fallback level by using its risk-based approach instead of fixed dependencies that have to be fulfilled. Flank protection requirements are often a problem in case of a failure. In current interlocking systems, a malfunction of a flank protection element often prevents the ability to send a movement authority to a train.

In many of those cases, a flank collision is very unlikely because

- there is reliable information that the relevant track area (flank protection area) is not occupied,
- only fully supervised trains are in the relevant track area, so that ETCS could prevent the trains from entering the potential flank collision hazard area,
- there is another element which provides flank protection, but due to the malfunction of the original flank protection element, the flank protection function cannot be transferred to this element.

In scenario 7, point 18 has a malfunction (cf. Figure 12). Therefore, a conventional interlocking system would prevent to set the yellow train route. A manual fallback procedure would be necessary. Due to the risk-based approach in the new interlocking system, the interlocking system could determine the risk of a flank collision on a basis of generic rules and the current operational situation. In scenario 7, point 19 could provide the flank protection if we assume that the new interlocking system knows with a sufficient certainty that the track area between point 19 and point 14 is free. Therefore, the yellow train can proceed as planned.

9 Quantification of the benefits

The paper describes the operational benefits in the seven examples qualitatively. The quantitative effects are highly dependent on the input parameters such as the infrastructure layout (especially the distance between scheduled stopping locations and danger points), the trains' characteristics as well as the planned timetable and momentary delays.

Currently, the research team at TU Darmstadt is conducting simulation runs with different trains using the example infrastructure in the railway operations centre Darmstadt to obtain quantitative data. The acceleration and braking behaviour of the trains is calculated by means of a multistep delta time approach according to the characteristics of the traction unit and the total weight of the train. The simulated train runs follow the permissible speed profile of ETCS level 2 with additional smoothing factors (below the allowed speed) to obtain a more realistic driving behaviour (e.g. to prevent the train from switching directly from a tight acceleration to a sharp braking). The simulation runs differ, among other factors, in terms of different train characteristics, the degree of localisation accuracy, length of the overlap, allowed speed profiles and the initial speed of the trains before entering the area under consideration as well as time differences between the arrival times of the different trains.

First results indicate that trains whose running path is occupied by another train could pass the sample station in many of the sample situations in significantly shorter time (up to 90 seconds compared to a reference scenario with ETCS level 2 and a conventional electronic interlocking; in comparison to a scenario without ETCS level 2, the benefit is even greater). Especially in highly frequented nodes (e.g. nodes of an integrated clock-face schedule), just a few seconds can decide whether delays continue to build up. We expect to have a first comprehensive set of quantitative results by the end of October 2021.

10 Conclusion

The presented operational benefits exemplify that an interlocking system which supports dynamic route assignment enables different positive effects on capacity. It reduces occupancy times and enables reducing buffer times by minimising the effects of operational disturbances. Especially the possibility to set the end of the movement authority (EoA) as well as the supervised location (SvL) to any location on the track network, a flexible handling of overlaps, and the risk-based flank protection approach could be beneficial. The effect on real-time operation might be even greater than the effect on the planning because in case of delays or malfunctions, flexible solutions to assign the track infrastructure can be used that do not exist today.

Some benefits presented in the scenarios (especially in relation to additional possible locations for the EoA or SvL) could also be realised with additional infrastructure (e.g. additional signals, points or trackside detection system elements) or additional planning effort. However, due to the priority 3 goals from chapter 4, this alternative realisation possibility is often not used in practice because the planning and certification cost would be too high or the process would take too long. Furthermore, additional infrastructure elements are also an additional source of malfunctions, which could decrease the reliability of the system. Due to these reasons, a generic approach has some advantages.

In order to implement an interlocking system with dynamic route assignment, a robust migration concept is vital that includes compatibility to older technologies like trackside train integrity monitoring. Otherwise, the migration could fail for railways with grown structures due to a step size that is too large. However, to reach the full capacity effects, a combination of several new technologies would be necessary. Such technologies include an ATC like ETCS, the new interlocking system, a precise localisation technology, a reliable communication technology, a Traffic Management System, which plans the route assignments for the interlocking system, and Automatic Train Operation (ATO), which ensures that the trains follow the assigned speed profiles.

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