RAILWAY INTERLOCKING PROCESS: A FORMAL METHOD FOR DOCUMENTING AND EVALUATING RAILWAY JUNCTION SIGNALLING AND INTERLOCKING

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Section 6.2.4 $\overline{v}_{s}$ The average speed when train travels between passing loop 1 and railway junction
Section 6.2.4 $\Delta s_{ij}$ Railway junction length
Section 6.2.4 $\overline{v}_{s}$ The average speed when train travels on railway junction
Section 6.2.4 $\Delta s_{ij}$ Section’s length between rail spur and railway junction
Section 6.2.4 $\overline{v}_{s}$ The average speed when train travels between railway junction and the rail spur
Section 6.2.4 $\overline{v}_{s_1}$ The average maximum speed when train travels on the rail spur
Section 6.2.4 $\overline{v}_{s_2}$ The average maximum speed on the rail spur when train is being loaded with coal
Section 6.2.4 $\overline{v}_{s_3}$ The average maximum speed when train travels on the rail spur toward the exit

Section 7 $C_{SS}$ Railway junction signalling system cost
Section 7 $F_{RI}$ Railway interlocking functionality
Section 7 $R$ Reliability
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Section 7 $C_{SS}$ Railway signalling system availability
Section 7 $R_{TSS}$ Theoretical railway signalling system reliability
Section 7 $R_{PRSS}$ Practical railway signalling system reliability

Section 7.1.1 $T_{IP,MP}$ Manual (human) interlocking processing time
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Section 7.1.1 $T_{b}$ Checking points position time $[T_{IP,MP}]$
Section 7.1.1 $T_{c}$ Displaying proceed aspect time $[T_{IP,MP}]$
Section 7.1.1 $T_{g}$ Proceed train time $[T_{IP,MP}]$
Section 7.1.1 $T_{h}$ Time to prepare route for approaching train $[T_{IP,MP}]$
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Section 7.1.1 $T_{y}$ Changing points position time $[T_{IP,MP}]$
Section 7.1.1 $T_{s}$ Points movement system fault time $[T_{IP,MP}]$
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Section 7.1.2.1 $T_{y}$ Insert operator’s key time $[T_{IP,MP}]$
Section 7.1.2.1 $T_{r}$ Turn operator’s key to unlock lever 1 time $[T_{IP,MP}]$
Section 7.1.2.1 $T_{t}$ Move lever 1 to opposite position time $[T_{IP,MP}]$
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Mechanical points and semaphores therefore any technical problem with semaphore S2 checking for any technical problem with pulling lever 2, mechanical points and semaphores fault until fault has been removed keeping interlocking in the state Points movement system mechanical points and semaphores position searching for any technical problem when changing points mechanical points and semaphores c checking the set of points is not occupied by any train and mechanical points interlocking arms horizontal positions searching for any technical problem with those semaphores' junction stopping any potential train movements through the railway mechanical points interlocking function: c checking the lever 5 can be moved mechanical points interlocking function: c checking that the route M<->N is being prepared mechanical points interlocking function: c checking the route M<->R is being prepared? mechanical points interlocking function: c checking the points are positioned normal mechanical points interlocking function: c checking the points are positioned reverse mechanical points interlocking function: c searching for any technical problem when changing points position mechanical points interlocking function: c keeping interlocking in the state Points movement system fault until fault has been removed mechanical points interlocking function: c checking for any technical problem with pulling lever 2, therefore any technical problem with semaphore S2 mechanical points interlocking function: c checking semaphore 2 system fault has been removed.
This function keeps the interlocking in this state - function:
- checking there is any potential train movement from S2 -> R being authorised

Section 7.3.2.2  F\text{XIV}  
Mechanical points and semaphores interlocking – function:
- checking S2 proceed aspect is displayed

Section 7.3.2.2  F\text{XV}  
Mechanical points and semaphores interlocking – function:
- checking the train has passed the railway junction leaving the points unoccupied

Section 7.3.2.2  F\text{XVI}  
Mechanical points and semaphores interlocking – function:
- checking there are no trains approaching the railway junction points

Section 7.3.2.2  F\text{XVII}  
Mechanical points and semaphores interlocking – function:
- checking the train has passed the railway junction leaving the points unoccupied

Section 7.3.2.2  F\text{XVIII}  
Mechanical points and semaphores interlocking – function:
- checking the train movement from S4 -> M is being authorised

Section 7.3.2.2  F\text{XIX}  
Mechanical points and semaphores interlocking – function:
- checking S4 proceed aspect is displayed

Section 7.3.2.2  F\text{XX}  
Mechanical points and semaphores interlocking – function:
- checking the train has passed the railway junction and the points are not occupied

Section 7.3.2.2  F\text{XXI}  
Mechanical points and semaphores interlocking – function:
- checking for any technical problem when pulling lever 4, therefore problems with semaphore 4

Section 7.3.2.2  F\text{XXII}  
Mechanical points and semaphores interlocking – function:
- keeping interlocking in the Semaphore 4 system fault state until fault has been removed

Section 7.3.2.2  F\text{XXIII}  
Mechanical points and semaphores interlocking – function:
- checking for any technical problem with points when changing their position

Section 7.3.2.2  F\text{XXIV}  
Mechanical points and semaphores interlocking – function:
- keeping interlocking the state of Points movement system fault until fault has been removed

Section 7.3.2.2  F\text{XXV}  
Mechanical points and semaphores interlocking – function:
- checking the points are in reverse position

Section 7.3.2.2  F\text{XXVI}  
Mechanical points and semaphores interlocking – function:
- checking the points are in normal position

Section 7.3.2.2  F\text{XXVII}  
Mechanical points and semaphores interlocking – function:
- checking train has passed the railway junction and the points are no longer occupied

Section 7.3.2.2  F\text{XXVIII}  
Mechanical points and semaphores interlocking – function:
- checking the train movement from S1 -> N is being authorised

Section 7.3.2.2  F\text{XXIX}  
Mechanical points and semaphores interlocking – function:
- checking S1 proceed aspect on semaphore S1 has been displayed

Section 7.3.2.2  F\text{XXX}  
Mechanical points and semaphores interlocking – function:
- checking train has passed the railway junction and the points are no longer occupied

Section 7.3.2.2  F\text{XXXI}  
Mechanical points and semaphores interlocking – function:
- checking for any technical problems when pulling lever 1, therefore any problems with semaphore 1

Section 7.3.2.2  F\text{XXXII}  
Mechanical points and semaphores interlocking – function:
- checking semaphore 1 system fault has been removed

Section 7.3.2.2  F\text{XXXIII}  
Mechanical points and semaphores interlocking – function:
- checking the train movement from S3 -> M is being authorised

Section 7.3.2.2  F\text{XXXIV}  
Mechanical points and semaphores interlocking – function:
- checking semaphore S3 proceed aspect has been displayed

Section 7.3.2.2  F\text{XXXV}  
Mechanical points and semaphores interlocking – function:
- checking train has passed the railway junction and the points are not occupied

Section 7.3.2.2  F\text{XXXVI}  
Mechanical points and semaphores interlocking – function:
- keeping interlocking in Semaphore 3 system fault until system fault has been removed
Section 7.3.2.2 \( F_{\text{xxxvii}} \) Mechanical points and semaphores interlocking – function: checking for any technical problem when unlocking lever 5

Section 7.3.2.2 \( F_{\text{xxxviii}} \) Mechanical points and semaphores interlocking – function: keeping interlocking in the state of Lever 5 system fault until system fault has been removed

Section 7.3.3 \( F_1 \) Electrically powered interlocking – function: identifying set a route request

Section 7.3.3 \( F_{Ii} \) Electrically powered interlocking – function: checking for any Reverse points request

Section 7.3.3 \( F_{Iii} \) Electrically powered interlocking – function: identifying if the route S1->N is being selected

Section 7.3.3 \( F_{Iv} \) Electrically powered interlocking – function: checking the route S1->N is available

Section 7.3.3 \( F_{V} \) Electrically powered interlocking – function: identifying if the route S3->M is being selected

Section 7.3.3 \( F_{VI} \) Electrically powered interlocking – function: checking the route S3->M is available

Section 7.3.3 \( F_{VII} \) Electrically powered interlocking – function: identifying if the route S1->R is being selected

Section 7.3.3 \( F_{VIII} \) Electrically powered interlocking – function: checking the route S1->R is available

Section 7.3.3 \( F_{IX} \) Electrically powered interlocking – function: identifying if the route S4->M is being selected

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Section 7.3.3 \( F_{XII} \) Electrically powered interlocking – function: checking the route S3->M or S1->R or S4->M are pre-selected

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Section 7.3.3 \( F_{XIV} \) Electrically powered interlocking – function: searching for any technical problems at pre-selection route S1->N

Section 7.3.3 \( F_{XV} \) Electrically powered interlocking – function: keeping interlocking in the state S1 Red aspect fault until signal S1 Red aspect fault has been removed

Section 7.3.3 \( F_{XVI} \) Electrically powered interlocking – function: checking if the route S1->N is pre-selected

Section 7.3.3 \( F_{XVII} \) Electrically powered interlocking – function: checking the tracks 2T, 3T, 4T and 5T are working properly and are not occupied

Section 7.3.3 \( F_{XVIII} \) Electrically powered interlocking – function: searching for any route request cancellation when checking track availability

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Section 7.3.3 \( F_{XXIII} \) Electrically powered interlocking – function: checking the points P1 are locked and detected in Normal position

Section 7.3.3 \( F_{XXIV} \) Electrically powered interlocking – function: checking the route S3->M or S1->R or S4->M has been locked

Section 7.3.3 \( F_{XXV} \) Electrically powered interlocking – function: searching for any request to cancel a route at checking the opposite route set

Section 7.3.3 \( F_{XXVI} \) Electrically powered interlocking – function: checking signal S1 is technically able to display proceed aspect

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Section 7.3.3  F_{XXXVII}  Electrically powered interlocking – function: keeping the interlocking in the state S1 Red aspect fault until signal S1 Red aspect fault has been removed
Section 7.3.3  F_{XXXVIII}  Electrically powered interlocking – function: searching for any technical problems associated with displaying red aspect on signal S1
Section 7.3.3  F_{XXXIX}  Electrically powered interlocking – function: keeping the interlocking in the state S1 Red aspect fault until signal S1 Red aspect fault has been removed
Section 7.3.3  F_{XXXX}  Electrically powered interlocking – function: checking any technical problem associated with Red aspect on signal S1
Section 7.3.3  F_{XXXXI}  Electrically powered interlocking – function: searching any request to cancel a route in the state of Displaying proceed aspect on signal S1
Section 7.3.3  F_{XXXXII}  Electrically powered interlocking – function: keeping the interlocking in the state S1 Red aspect fault until signal S1 Red aspect fault has been removed
Section 7.3.3  F_{XXXXIII}  Electrically powered interlocking – function: searching for any technical problem when cancelling points request R->N
Section 7.3.3  F_{XXXXIV}  Electrically powered interlocking – function: keeping the interlocking in the state of Points system fault until points P1 movement system fault has been removed
Section 7.3.3  F_{XXXXV}  Electrically powered interlocking – function: checking the points P1 are locked and detected in Normal position
Section 7.3.3  F_{XXXXVI}  Electrically powered interlocking – function: searching any technical problem when controlling points Normal (R->N)
Section 7.3.3  F_{XXXXVII}  Electrically powered interlocking – function: keeping the interlocking in the state S1 Red aspect fault until signal S1 Red aspect fault has been removed
Section 7.3.3  F_{XXXXVIII}  Electrically powered interlocking – function: searching any technical problems associated with displaying red aspect on signal S1
Section 7.3.3  F_{XXXXIX}  Electrically powered interlocking – function: searching for any technical problem when controlling points Normal (R->N)
Section 7.3.3  F_{XXXXX}  Electrically powered interlocking – function: searching for any technical problem when displaying red aspect on signal S1
Section 7.3.3  F_{XXXXXI}  Electrically powered interlocking – function: checking any route is pre-selected or locked
Section 7.3.3  F_{XXXXII}  Electrically powered interlocking – function: checking the points P1 are detected Reverse
Section 7.3.3  F_{XXXXIII}  Electrically powered interlocking – function: searching for any technical problem when cancelling points request R->N
Section 7.3.3  F_{XXXXIV}  Electrically powered interlocking – function: keeping the interlocking in the state of Points system fault until points P1 movement system fault has been removed
Section 7.3.3  F_{XXXXV}  Electrically powered interlocking – function: checking the points P1 are locked and detected in Normal position
Section 7.3.3  F_{XXXXVI}  Electrically powered interlocking – function: searching any technical problem when controlling points Normal (R->N)
Statement of originality

This work has not previously been submitted for a degree or diploma in any university. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made in the thesis itself.

SIGNATURE
Acknowledgment

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Biography

Jacek Mocki is highly experienced Transport professional conducting research for a higher degree (PhD) at the Intelligent Control Systems Laboratory of Griffith University. Working at the same time with Siemens Rail Automation as a Business Development Manager, Jacek is currently improving rail Transport reliability in Queensland and Hunter Valley.

He has planned, developed and delivered railway projects and control systems from concept to feasibility through to detailed design within a multidisciplinary railway engineering environment in Europe, the UK and Australia.

Jacek has published and presented a number of scientific papers on various international conferences in Germany, Bulgaria, Poland, Russia and China as well as International Journals.

His practical approach supported by the industry inside, combined with highly regarded scientific knowledge and effective communication skills delivers quite unique and positive results in his research as well as professionally when improving rail transport reliability. Just recently, Jacek has introduced a points condition monitoring system to Queensland customers, successfully implementing the system on most critical points. The system defines the causes of faults that used to be defined and categorised as “fault – no fault found”.

He graduated from the Warsaw University of Technology in 2000 (Transport Engineering) completing at the same time his MSc in Transport.
Executive summary

Railway junctions have been signalled in many different ways using various railway interlocking and signalling technologies. Implementations of those technologies are not identical and are customised for every railway junction. It is therefore very difficult to consistently compare various signalling and interlocking technologies using currently available methods. That creates an enormous task for transport and/or signalling planners to propose the technology that meets the operational conditions on a specific railway junction.

This thesis enhances the signalling and interlocking planning process by developing a formal method for documenting and evaluating railway junction signalling and interlocking. More precisely, it makes the following contributions:

- It develops a structured method to enable railway transport planners to evident a specific railway junction arrangement and, in response to it, determine and describe a corresponding signalling and interlocking algorithm. This includes characterisation of:
  - manual interlocking algorithm
  - mechanical interlocking algorithm
  - electrically powered interlocking algorithm.

- It develops an analytical model to calculate the railway junction’s interlocking and signalling requirements determined by the track arrangement installed, such as:
  - minimum travel distance
  - maximum velocity
  - minimum train travel time in the track arrangement.

- It defines performance measures relevant in the railway interlocking evaluation process, such as interlocking processing time, signalling system cost, interlocking functionality, signalling system availability and reliability. These operational performance measures allow consistent comparison and evaluation of the interlocking on a railway junction.

It is believed that this thesis is the first of its kind which offers a formal method for consistent and comprehensive comparison of signalling and interlocking technologies from the viewpoint of the specific railway junction operational requirements and performance measures.

Within the set research framework, the developed formal method deals with signalling and interlocking implementations on a single, bi-directional railway junction only.

By the time of writing this thesis the four conference and journal papers have been published i.e. submitted for publishing.
1. Motivation

The inspiration for this thesis stems from the longstanding engagement of the thesis author with railway transport systems who witnessed that transport planners often postpone their decision on the specific railway interlocking technology to the signalling system implementation phase due to:

- the lack of publicly available railway signalling and railway interlocking technology selection tools that could be used to develop requirements for signalling and interlocking at the planning phase

- the fact that the popular RAMS (Reliability, Availability, Maintainability, Safety) concept, which is aimed at evaluating railway signalling systems, is not normally applicable to the analysis of a railway junction’s operational conditions and to the task of establishing railway junction performance measures

- the fact that currently published literature elaborates mainly on formal methods to specify interlocking or/and verify interlocking. There is no method available to consistently and comprehensively compare signalling and interlocking technologies to be implemented on a railway junction.

The implementation of signalling & interlocking systems is often delayed and their ability to entirely fulfil specific operational requirements for each and every railway junction is not always guaranteed.

It is believed that this thesis is the first of its kind which offers a formal method for consistent and comprehensive comparison of signalling and interlocking technologies from the viewpoint of the specific railway junction operational requirements and performance measures.

Being a railway system practitioner, the PhD candidate has seen many pieces of work spoilt by unrealistic models, incorrect axioms or proofs of irrelevant properties. Since I am of the view that the modelling of systems, as well as proof obligations, need to be faithful, I was committed to the goal of developing a formal method which is to be equally useful in both the modelling world and the real engineering world. Thus, the developed formal method, described in this thesis, is built from the viewpoint of the railway system practitioners, both the operators and designers of the railway junction signalling and interlocking solutions.

Within the set research framework, the developed formal method deals with signalling and interlocking implementations on a single, bi-directional railway junction only.

The thesis is organised in such a way that Chapter 1 introduces the general problem, Chapter 2 justifies the research providing literature evidence of what formal methods are available in railway signalling and interlocking. Chapter 3 describes the basics of a railway junction with track arrangement, discussing a variety of configurations with a crossover, a railway station, a passing loop and a rail spur. Chapter 4 describes railway signalling terms with its components and railway
interlocking with a on the most important aspects. Chapter 5 elaborates on currently implemented interlocking and signalling on railway junctions, categorises the interlocking and defines interlocking processes for those implementations.

Next in Chapter 6, railway junctions’ operational conditions are introduced and discussed to specify requirements for interlocking on a railway junction. It defines analytical models for the calculation of a railway junction’s requirements including minimum distance, maximum velocity and minimum train travel time for the given track arrangement, thus enabling transport planners to build a train travel chart that graphically describes the required train operations with a special attention to interlocking processing time requirements. It presents the outcomes obtained from the use of the developed methodology in a coal transportation planning task within the framework of one of our most recent railway junction signalling & interlocking coal transport projects in Australia.

Moreover, Chapter 7 describes railway interlocking performance measures to be able to assess interlocking technologies to meet the requirements specified by operational conditions on a railway junction. The formal method has been developed for the purpose of comparing various technology implementations on a single, bidirectional railway junction.

Chapter 8 summarises the formal method delivering some guidance on how to actually use it in practice.

Chapter 9 of the thesis discusses the applicability of the method for a variety of railway junctions to demonstrate that the method is universal and transport planners can consider applying it to set requirements of railway signalling and interlocking technology and even commence the railway interlocking technology selection process in the transportation planning stage to achieve efficient investment.

The thesis is concluded with Chapter 10 - Discussions and concluding remarks.

Chapter 11 highlights the contributions of this thesis and finally Chapter 12 provides some indication of how the formal method introduced by this thesis could be further developed.
2. Research into formal methods

This Chapter elaborates on formal methods for railway signalling and interlocking currently available and justifies the need for this research.

Reviewing the railway interlocking literature published so far [1]-[44], the formal methods can be grouped into the following categories:

- Trends in formal methods, [1], [2]
- Specification and design of railway interlocking, [3]-[25]
- Modelling of railway interlocking, [26]-[31]
- Validation and verification of railway interlocking, [32]-[35]
- Evaluation of railway signalling and interlocking and RAMS (Reliability, Availability, Maintainability, Safety), [36]-[44].

This thesis is related to the railway interlocking process and a development of a formal method for documenting and evaluating railway junction signalling and interlocking.

2.1. Trends and formal methods

There are a few key statements found in literature that confirm the need for formal methods and justify their constant evolution and development in railway signalling and interlocking:

“Since more than 25 years, railway signalling is the subject of successful industrial application of formal methods in the development and verification of its computerized equipment. The scope of the formal methods discipline has enlarged from the methodological provably correct software construction of the beginnings to the analysis and modelling of increasingly complex systems, always on the edge of the ever improving capacity of the analysis tools, thanks to the technological advances in formal verification of both qualitative and quantitative properties of such complex systems.” [1]

“On the one hand, railway interlocking has always generated the interest of formal methods researchers, due to its safety-criticality, and the absence of complex computations and hard real-time constraints, making it a promising application field. On the other hand, railways have always had a very strong safety culture, based on simple fail-safe principles. In electro-mechanical equipment, used in most signalling systems before the introduction of computers, gravity was used to bring a system to the fail-safe state (e.g. all signals to red) in any occurrence of a critical event. The fact that computers have no gravity, that is, the impossibility of predicting in general the effects of the occurrence of faults, has long delayed the acceptance of computer-controlled signalling equipment by railway companies. The employment of very stable technology and the quest for the highest possible guarantees have been
key aspects for the adoption of computer-controlled equipment in railway applications. Formal proof, or verification, of safety is therefore seen as a necessity.” [2]

“The evolution of formal methods and formal verification tools themselves opens new possibilities to tackle the complexity of these systems, not only for safety certification, but also for other dependability issues. Formal modelling can even act as a facilitator for railway signalling innovations.” [2]

2.2. Specification and design of railway interlocking

Signalling principles and implementations of signalling and interlocking systems on a railway junction have been widely studied. Examples can be found in [3]-[25]. The literature elaborates on the general rules applied to railway signalling interlocking [5], [6], [7], [9], [10], [15], [16], i.e. it describes in great detail the principles on which trains can operate, eliminating the risk of colliding. It defines the elements of a signalling and interlocking system [3]-[16], formalises the nomenclature for future development of signalling [3], [4], [5], [6], [7], [15], compares principles and operational rules/requirements in various countries [5] and presents some railway interlocking technology [3]-[16].

In searching for formal methods, the scientists initially started formalising specification and design of railway interlocking. Studies are focused on descriptions of various technologies used in the railway interlocking. For example, L. Zigterman in [17] documents types of interlocking used till 1980; he describes mechanical, electro-mechanical, all-relay systems (including geographical circuitry) implemented by relay technology. The paper summarises the technologies and documents developments in the 1980s. In the railway technology section, it defines basic equipment, train movements, individual control and operating procedures.

It can be also observed that literature [17][18] has been talking about formal methods to specify and design railway interlocking logic since the signalling engineering seriously considered computer based interlocking applications.

L. Zigterman describes computer languages that can be used to specify and design railway interlocking, including Pascal, Modula, CHILL and Ada. All those languages are concluded as meeting the criteria of structured programming, data definition constructs and concurrency. [17] While those languages are still in use and many new languages are also applied, current works on computer based interlocking languages are focused on formalising signalling principles to automatically generate interlocking logic specific for certain computer based interlocking technology. [18]

“Writing interlocking logic is an important part of designing a railway interlocking system.” [19] In this reference, “a new method which increases the efficiency of writing interlocking logic is introduced. That is describing interlocking rules and station topology separately, and producing interlocking logic automatically by associating topology data with interlocking rules using software tools. As interlocking rules remain the same, the work for a new station is to specify the topology data
only and the new interlocking logic can be generated automatically. This paper emphasizes on a component-based model used to describe the topology of the station." \[19\]

Another interesting approach is presented in \[20\] where the authors specify a geographical railway interlocking system using statecharts to be able to distribute the interlocking functions “in the field”. Then they apply tools like Stateflow (MmathWorks), Telelogic TAU Generation 2 (Telelogic), RealTime Studio (Artisan Software), visualSTATE (IAR Systems) to model and assess the safety of the distributed railway interlocking system.

S. Bacherini, A. Fantechi, M. Tempestini, N. Zingoni also talk about statecharts (stateflow). They provide some evidence that using “Stateflow component of Matlab” has been adopted by General Electric Transportation Systems at “modelling environment as the main formalism … to write formal specification of railway signalling products”. \[21\]

There have been many attempts to produce standards on formal methods. The study by Söylemez, \[22\] refers to European standards EN 61508-3 and EN 50128. They highly recommend the use of formal and semi-formal methods in the design of safety critical software where SIL 3 or more is targeted. Unfortunately, those standards are related to software interlocking only and not formalising mechanical, electro-mechanical and relay interlocking.

An extremely relevant publication by H. M. Schulz describes some examples from industrial projects in automotive embedded systems and railway traffic control systems and discusses if formal methods can play a role in requirements engineering. The author presents his view on: role and access management on example of European railway CENELEC standard 50126, exchange of requirements documents and linking of requirements. The conclusion of the publication is one of the reasons this thesis will be extremely useful for future developments in railway interlocking and signalling. H. M. Schulz says: “the last years of defining and implementing processes in industrial practice have shown to the author that there is a large potential for formal measures in the specification processes. Lack of tool support, incomplete understanding of the cost and gains by the involved stakeholders did not yet allow their widespread use. Nevertheless, it is the strong belief of the author, that without better specification documents and processes, subsequent formal models and tools – which are without doubt powerful and useful – are inefficient to apply and will not show their potential”. \[23\]

J. Peleska in his post-doctoral thesis \[24\] talks about formal methods and the development of dependable systems, which signalling is a perfect example of. His post-doctoral thesis focuses on showing how a new combination of existing formal methods in software specification can be applied more efficiently to solve problems in the field of dependable systems. There is an important statement in his work which also may be applicable to interlocking logic specified in software: “the motivation to use theory for building software was purely motivated by the fact that the informal heuristics applied for constructive or analytic software quality assurance are completely insufficient when applied to systems where correctness of software really matters”. \[24\]
E. Roanes-Lozano, A. Hernando, J. A. Alonso, L. M. Laita in their publication [25] took a very practical approach to specify a new model, based on Boolean Logic, that is independent from the topology of the analysed station. They pay particular attention to the formalism of a railway interlocking system detailing the rules of the interlocking for a particular simple railway loop ("a very simple station" [25]), illustrating the rules with an example to further define the rules before building a model. The proposed model is based on propositional logic allowing detection if a section of track is safe and if the whole network is safe. The implementation of that model is written in a computer algebra system called Maple [25].

2.3. Modelling of railway interlocking

Another important group of formal methods is related to modelling of railway interlocking systems. The main reason for modelling is to be able to automatically analyse safety features of interlocking and be able to automatically and scientifically prove a sufficient level of interlocking safety.

In [26], the Vital Processor Interlocking (an interlocking system originally developed by the Engineering Department and the Rail Infrabeheer Department of the Dutch Railway Company) is modelled using μCRL. “A VPI can be characterized as a Programmable Logic Controller (PLC) that is tuned for use in a railway environment. The most important application software loaded into a VPI is called the Vital Logic Code (VLC).” [26] The author used the semantics of μCRL specification to model VPI, a system used at Dutch railway yards. Furthermore, he formulated a collection of correctness criteria in μCRL. Later on to automate verification, a number of tools were specified in ASF+SDF (a term rewriting language that extends the syntax definition formalism SDF (Syntax Definition Formalism)) and they were implemented in C computer language. [26] The author concludes the paper with a statement that the model can be implemented in the current VPI engineering process as an additional check, especially in the collation process.

A different reason for modelling is presented in [27] where Ronghui Liu, Anthony Whiteing and Andrew Koh look into challenging established rules for train control on a railway junction. The authors use a fault tolerant approach. They formalise elements of signalling system involved in train control on a railway junction, they define changes to the operational rules that do not compromise safety but may improve efficiency of train operations. Analysed currently available commercial modelling and simulation tools like OpenTrack, RailSys, SimMETRO and VISIONS have been disqualified from application due to their design (covering only existing rules). With modified operational rules, the authors have adopted the road-based simulation model DRACULA to the railway domain and new modelling features to represent railway blocks, overlaps, points and the three-aspect signal signalling system described above. The model takes into account the line speed limits, and the normal operating speed of relevant rolling stock and its acceleration and deceleration rates. The authors demonstrated a single example of the potential capacity gain by relaxing the rules of railway operation in the single situation of a railway junction. They also refer the changes to operational rules as “significant hurdles to overcome before such principles can be adopted” even modelling reflects it is worth looking at. [27]
An alternative method, a decision support “methodology for real-time train re-scheduling in junction areas”, is discussed in [28]. This kind of modelling that enhances the management of train operations to ensure optimum use of the available capacity and to minimise disruption to services following minor incidents [28] has a very practical approach. This is a great method that can be applied when designing an application of railway train control system. There can be some additional performance measures considered to enhance meeting capacity requirements and optimise infrastructure investment that will be described further down in this thesis. Those performance measures can enhance the selection of a railway signalling and interlocking system.

“Modelling railway interlocking system present a formal model of railway interlocking systems following a protocol based on train routes. The model is divided into one part describing the physical system and another part describing the control mechanisms monitoring observables of the physical system. The safety requirements are formalised at a high level of abstraction and it is then verified that the protocol (concrete safety requirements) ensures safety.” [29]

Anne E. Haxthausen, Marie Le Bliguet and Andreas A. Kjær have modelled a relay interlocking system based on Danish interlocking principles. The principle of Danish interlocking is train route based. The authors have described and graphically presented the principles. Later on, ladder diagrams [30] have been used and the nomenclature of diagrams defined to transit the formalisation of relay interlocking logic to a set of computer instructions. Finally, the authors have conducted an experiment on interlocking of Stenstrup railway station that included 46 internal and 10 external relays. The transition system model contained more than 61 Boolean variables, 92 transition rules for internal relays and additional rules for the environment. There have been 100 confidence conditions and 36 safety conditions. The model has been verified using RAISE tools and SAL model checker. [29][30] The main reason for modelling in this case is to automate the verification process of railway interlocking.

2.4. Validation and verification of railway interlocking

“Formal methods for specification and verification are slowly and with difficulties reaching some appreciation and use in the industrial environment: there are many notations, methods, and (prototypical) tools originating from the academia, which however lack industrial strength in terms of tool stability, documentation and user support; on the other hand, there are very few technically sound methods and tools coming from industry.” [2]

There is some evidence of formal methods in the literature where relay interlocking is mentioned, however, this is in relation to validation and verification of railway interlocking only. Anne E. Haxthausen in [31] takes a very interesting approach in searching for a formal verification of relay interlocking using a framework of computer-based tools that support the validation and verification process.
The main focus of validation and verification of railway interlocking is for specific programming language in specific computer based interlocking.

J. L. Petersen in [32] describes mathematical methods for validating railway interlocking systems using STERNOL language. STERNOL is a programming language to prepare an EBILOCK interlocking logic data. Once again, a specific language in a specific computer based interlocking.

T. Hlavaty and S. Klapka [33] present their work on formal methods in development and testing of safety critical systems: railway interlocking system. The literature conducts an extensive review of formal methods that could be utilised for proper software specification, design and verification of safety properties of railway interlocking system (computer based interlocking). The discussion is conducted using an example of a real interlocking system for Line Block (LB) developed by AZD Prague Ltd.

S. Bisanz, P. Ziemann, A. Lindow propose “the integration of the HybridUML specification formalism and the USE approach for validation of invariant constraints and verification of system states. The benefit is an executable real-time simulation with an integrated verification/validation component, which combines the advantages of the previously separate approaches by providing an accurate, (partially) time-continues model that can be checked for consistency between static invariants and dynamical behaviour in terms of a complete UML model. The integration is illustrated by means of train system specification” [34]

The literature also provides some guidance on the practicality of formal methods and their faithfulness: “Faithfulness relates to a variety of concerns. Axioms must be traceable to the informal domain description. The model must be formulated in a way that the reader can maintain a clear overview. The model must provide the right level of abstraction for the properties to be shown: details that cannot destroy the property should be left out; it must be possible for the properties to hold or to be wrong. The proof steps should have a meaningful interpretation within the original domain (an invariant has a meaning in the real world). The formal model should be accessible to the domain experts (under minimal guidance). Finally, it should be easy to switch between the real world and the modelling world.” [35]

2.5. Evaluation of railway signalling and interlocking and RAMS (Reliability, Availability, Maintainability, Safety)

The evolution of signalling is more than a century old. There is quite a significant number of various signalling and interlocking systems deployed on railways all over the world. A number of companies, railway system designers and operators have developed and implemented their solutions to railway signalling and interlocking. With such wide technology availability, the rail operators face a dilemma, at the investment decision-making stage, as to which interlocking type should be invested into, how to assess the technology and what performance measures to use for the purpose of comparing various technologies and selecting the most appropriate one.
However, there are very few published papers that discuss the issue of evaluating real time performance of the signalling and interlocking implementations [36]. Typically, they are focused on one particular type of interlocking and its specific aspects.

A performance evaluation of railway computer interlocking system based on queuing theory has been presented in [36]. The authors are complementing computer based interlocking system over relay based interlocking excluding the relay interlocking from their performance evaluation. In Table 1 [36], they are presenting the performance and efficiency of certain interlocking functions processed in computer based interlocking. It would be great to see a similar table for an equivalent relay interlocking. Further in this paper, there is a number of ‘must have’ statements listed for computer based interlocking. The most important one: “the computer must be able to handle the concurrent events very quickly, otherwise the efficiency of the traffic in station will be decreased and even some dangerous damage may be caused, so the real-time performance is very important for the interlocking processor, especially with the increasing of functions and extending of the controlling scope” [36] opens up another evaluation discussion. Analysing the statement and looking into Table 1 [36], the reader may have the following questions: what the particular requirements, for the particular railway arrangement, in this particular transportation process should apply. Also, do they need to apply this sophisticated computer based interlocking to that railway arrangement while a relay interlocking that would meet those requirements (lower than those requirements presented in Table 1 [36]), would potentially deliver some significant savings of the capital and operational costs for that transportation process.

The paper itself is focused on a comparison of FCFS (First Come, First Served) model and NPPR models (models to evaluate the software real-time performance of the blocking processor) using some hypothetical requirements for real-time micro-processing of computer based interlocking [36]. The authors close the complex mathematical evaluation, conducted using NPPR and FCFS models, with a conclusion that “the model NPPR is prevail over model FCFS in real-time performance” [36] based on the assumptions in that paper.

Ikuo Watanabe, Yuji Hirao and Koji Iwata propose a quantitative evaluation method for safety of railway signalling systems. The paper presents a new safety analysis method for railway signalling systems and introduces component fault occurrence probability vector, functional failure probability vector, correlation matrix between functional failures and component faults, mitigating matrix, and several other factors. By using these factors, the authors could estimate the risk of signalling systems, the effectiveness of safety measures, dangerous system failure probability and other related values. They also introduced a new automatic train control system and safety technologies, and evaluated the effectiveness of these technologies by calculating the elements of mitigating matrix. [37] This approach delivers a very unique method to evaluate a railway signalling system, however, the method is being applied using a particular automatic train control system. It is not entirely clear if that method is applicable to other signalling systems. The paper also evaluates the effectiveness of that system from a safety and reliability perspective only. There is no discussion on effectiveness of application of the system and the user requirements (operational requirements) for such evaluation.
RAMS (Reliability, Availability, Maintainability and Safety) is widely applied to evaluate safety of interlocking. Literature examples [38]-[44] detail the approach. RAMS can also be used to evaluate the technical performance of interlocking, however, it is not designed to demonstrate the cost effectiveness or/and functionality of interlocking implementations. A more comprehensive approach needs to be undertaken when considering an interlocking investment on a railway junction.

Paper [38] – a method of evaluating railway signalling system based on the RAMS concept proposes a basic method to evaluate performance of a signalling system by a cost indicator based on the concept of RAMS and confirms that the method can evaluate systems appropriately considering grade of the line, circumstances and other factors. The proposed approach is simple: Estimating the impact on train operation caused by an equipment failure (a component of the signalling system) and convert the impact to a loss (cost). The authors assume the signalling system is based on proven safety technologies and the safety analysis achieves a sufficient level of safety, focusing on availability, which consists of reliability and maintainability. [38]

Kazue Yasuoka, Atsushi Watabe, Tetsunori Hattori and Masayuki Matsumoto in [39] present a proposal how to adopt RAMS for railway signalling system management. The idea of that approach is to utilise RAMS technique to improve performance, maintenance of signalling system and reduce failures. The authors evaluate railway signalling system reliability and risk related to system downtime. Then certain problems become clear and improvements can be made. The policy developed in [39] applies to the East Japan Railway Company, which includes 1,705 railway stations on 7,527 kilometres of the network in eastern Honshu, including the Tokyo metropolitan area.

Low Intrusion Validation Environment (LIVE) is a validation environment developed by Ansaldo-Cris to experimentally evaluate the dependability of the new families of computer based railway control systems. “LIVE integrates fault injection and software testing techniques to achieve an accurate and non-intrusive analysis of a system prototype.” This kind of evaluation is influenced by the need to ensure full compliance with the new dependability standards emerging for railway apparatus. [40]

The authors are effectively validating an automatic train control system in two phases: “dependability testing (fault removal) aimed at the discovery and correction of design errors in the management of the faults in hardware-software system prototypes and dependability evaluation (fault forecasting), combining the experimental results with analytical models in order to evaluate the Mean Time Between Hazardous Events (the rate with which the system is forecast to produce output that can lead to catastrophic effects for people or equipment).” [40] Even though the contribution to the railway signalling is quite significant and important, this paper does not evaluate cost effectiveness of the system application nor does it compare various technologies. It also does not deliver any method to set requirements for such application.
Dependability evaluation of a real railway interlocking device [41] presents an evaluation of a component of railway interlocking system – track circuit receiver - using Markov chain model for the reliability analysis. That evaluation is focused on validation of this particular part of railway interlocking related to track circuit rather than comparison of various technologies. The paper is focused on proving that designing equipment to fault-tolerant attribute is also an important part of safety assessment. “The authors are convinced that new designed interlocking devices should be designed as a fault-tolerant system”. [41]

An interesting method to assess and optimise dependability of complex macro-systems has been presented by David Vernex and François Vuille in [42]. Their developed method called FMECA (A functional failure mode, effects and criticality analysis) is designed to address the dependability optimisation of large and complex systems. In this paper the authors applied the methods to analyse a European Train Control System Level 2 on a bi-directional 37 kilometre tunnel through the Swiss Alps. That line absorbs 30,000 trains per year and has been in operation since 2007. “The proposed approach has been implemented on an innovative railway signalling and automated system. It did yield a global and joint view of the Availability and Safety performances of the system and did successfully highlight existing vulnerabilities in different phases of the system development. However, as it is always the case with innovative systems, the lack of relevant reliability data proved limiting for assessing certain aspects of the system.” [42] It is interesting how applying the FMECA method to other existing railway signalling and interlocking technologies where relevant reliability data is available would see the comparison between the technologies. The method needs to be also enhanced with few other important factors like system implementation cost, functionality and interlocking processing time requirements. It is extremely important to take methods like FMECA under consideration as Availability and Safety performance of the system tool when developing a method to compare railway signalling and interlocking technologies.

Koji Iwata, Shigeto Hiraguri and Ikuo Watanabe elaborate on their evaluation method for railway signalling systems from the viewpoint of availability [43][44]. This approach has already taken into consideration methods mentioned in two other papers: Markov model [41] and FMEA [42]. The authors propose the method to evaluate the mitigation effectiveness of each safety measure and to improve systems efficiently by comparing these potential measures. [37] The paper, apart from signalling system availability, takes into consideration some kind of costs:

- \( C_i \) related to an occurrence frequency per hour of a failure mode leading to safe-side failure \( a_i \)
- \( C_j \) related to an occurrence frequency per hour of a failure mode leading to danger-side failure \( s_j \),

calculating Risk (defined by a combination of the failure occurrence frequency per hour and the resulting loss) as a sum of availability multiplied by cost \( Risk = \sum(a_i \times C_i) + \sum(s_j \times C_j) \). Based on the risk factor for each line, the target values – such as the availability and safety of railway signalling systems on individual lines are determined. The authors also claim that it is very difficult to compare safety levels with cost. [44] However, the difficulties are not elaborated on.
The method has three steps:

Step 1: Evaluation of current status (current availability, effect on current train schedule, current cost)

Step 2: Setting target values (target availability, target number of trains suspended or delayed, target cost)

Step 3: Determination of measures to be applied to attain the target availability (selection of target components for improvement and their effectiveness, effectiveness from the viewpoint of the whole system. [44]

The proposed method was presented on an example of Line A (around 50km long, 15 stations equipped with interlocking devices and used by 101 trains per hour during peak times on quadruple track at a typical station) and Line B (a distance of about 30km, 12 stations with interlocking devices, 9 trains per hour in both line direction during peak time at representative stations) with target availability 8.6h/year (Line A) and 321h/year (Line B) respectively for 2.6million persons/year. [44]

The authors of the evaluation of signalling system from the viewpoint of availability presented in [44] concluded their paper with a statement that further application of their method will facilitate the selection of measures to efficiently improve the availability of the system as a whole. Therefore, the entire method is focused on improvement of an existing signalling system rather than a comprehensive comparison of various signalling and interlocking technologies.

This literature review proves there is the need for developing the method presented in this thesis. Within the framework of the thesis, the method will address signalling and interlocking implementations on a single, bi-directional railway junction only.

3. Railway junction description

This chapter describes the basics of a railway junction with track arrangement, discussing variety of configurations with a crossover, a railway station, a passing loop and a rail spur.

A railway junction is a railway track arrangement made in such a way that a train changes direction to Normal (N) or Reverse (R) travelling from Main (M) or merges into Main when travelling from Normal or Reverse and the railway track arrangement is fully signalled. An example of a railway junction is presented on Figure 1. It is possible in a track arrangement that continuing the Normal direction track from the railway junction, the track can be connected to Reverse or Main. Also, extending the Reverse track from the railway junction it can be connected to Main.

When discussing various track arrangements in this section of this thesis, the signalling arrangements in the schematics of railway junctions will not be shown as various technologies may be implemented to signal the junction. The author would like to focus the reader on understanding the basic concept of the simplest railway junction.
Figure 1 An example of railway track arrangement that creates a railway junction

The example shows the simplest railway junction as is possible to imagine. This is built on a single, bidirectional section of track. Figure 2 simplifies the track of the railway junction from Figure 1, so that further analysis can be conducted. The track is shown schematically using a single line.

Figure 2 The railway junction from Figure 1 presented in a simplified way

The railway junctions can be more complicated and it can be analysed as part of a bigger track arrangement. For example an arrangement of two railway junctions in a two track arrangement can create a crossover (Figure 3) to connect those two tracks allowing a train to cross from one section of track (Down track) to the parallel, second section of track (Up track).

Figure 3 A crossover and a railway station arrangement of railway junctions

Developing further a crossover and a railway junction can provide the way for a train to cross from the ‘Down track’, through the ‘Up track’ to a third section of track (‘Third track’). Now, if the same arrangement is mirrored at the other side of a railway station, the train can return from the ‘Third track’ through the ‘Up track’ to the
‘Down track’. This kind of six railway junction arrangement can be defined as a railway station (Figure 3).

Railway junctions are used to create passing loops and rail spurs. A passing loop is an arrangement of two opposite railway junctions connected together with a second piece of track. A rail spur is an arrangement where only one railway junction is involved, the rail is extended in the normal direction of the junction and curves so that it joins the railway junction in the reverse direction.

Two passing loops and a rail spur in a single track, railway junction arrangement is shown on Figure 4. Passing loop 1 is connected to the railway junction from the main direction of the railway junction while passing loop 2 is connected to the railway junction from its normal direction. From its reverse direction there is a rail spur connected to the railway junction.

Figure 4 A railway junction within a rail arrangement

Complicating a little bit the Figure 4 arrangement of passing loop 2, a few more railway junctions can be added to create a more sophisticated railway loop or even a railway station (as shown on Figure 5).

Figure 5 A railway station arrangement within a rail arrangement

‘Railway station’ in this case will be defined as an arrangement of simple railway junctions with platforms that allows passenger train operations. ‘Train’ and ‘platform’ will be explained when discussing operational conditions.
4. Railway signalling and interlocking

This chapter describes railway signalling terms with its components and railway interlocking with a highlight on the most important aspects.

4.1. Railway signalling

Railway signalling\(^1\) is aimed at providing safe and secure train operations. The railway signalling system is a combination of signalling system components like semaphores or colour light signals, point mechanisms or point machines and train detection units built within railway track and controlled by a railway interlocking.

A semaphore is a mechanically operated arm mounted on the top of a post or a mechanical structure that provides a visual display to the train driver to proceed or stop the train. In new railway signalling installations semaphores are no longer used. Their functions have been fulfilled and enhanced by colour light signals.

A colour light signal (or ‘signal’ for short) is an electrically powered group of colour lights mounted on the top of a post that is installed near the railway track and arranged in such a way to display indications to the train driver. Those indications inform the train driver if a section of track behind the signal is clear for the train to proceed. The arrangement of colour lights depends on signalling principles and is always shown on signalling plans.

A point mechanism is an arrangement of mechanical components on a set of points done in such a way that a person can manually operate the points from normal to reverse or reverse to normal. In some signalling arrangements, point mechanisms are still the preferred option; however, on main lines point mechanisms are superseded with point machines.

A point machine is an electrically operated machine that remotely operates points from normal to reverse and reverse to normal.

A train detection unit is a device that provides information about the absence of trains.

This is also important to mention signalling principles. The essential purposes of a railway signalling system are:

- To maintain a safe distance between following trains on the same track
- To safeguard the movement of trains at junctions, and when crossing a path which could be taken by another
- To regulate the passage of trains according to the service density and speed required. [45]

\(^1\) The signalling industry incorporates signalling, interlocking and control systems under one and the same term – railway signalling.
It is also a fundamental requirement that in the event of equipment failure the safety of trains must be ensured. [45]

Those rules listed above are key to understanding the signalling principles. However, various countries in the World are implementing the fundamentals in various ways and even more within those countries various infrastructure owners/operators are implementing the fundamentals in various ways. Those rules are described in railway standards applicable for certain infrastructure owner/operator.

For example, in electrically powered interlocking, in countries like the UK there is a section of track called overlap introduced into the signalling principles to provide extra protection in the case a red aspect is passed at danger, while in Eastern Europe such a thing does not exist at all.

In the UK train drivers learn train speeds for the entire section of track and a board next to the track reminds them about the applicable maximum speed, while in Melbourne, Australia, colour light signals’ indications provide not only proceed or stop aspects but also inform train drivers about the train speed limit behind the signal.

There are obviously more differences between various signalling principles than listed in the examples above and it is important that interlocking process formalisms reflect the diversities.

4.2. Railway interlocking

Railway interlocking is a functional arrangement of apparatus that controls signalling system components to achieve safe, expected outcomes of controlling train movement.

Fail safe in railway signalling is a concept where a signalling system component being in safety critical fault condition will fail to the right side not causing any dangerous situation for train movements. The component of railway interlocking will provide in that case the highest possible level of security of train movement. For example if a train is approaching a signal and the signal cannot display a proceed aspect because the yellow lamp failed, the railway interlocking system will automatically display red aspect and stop the train instead of displaying a blank aspect that may confuse the train driver.

Historical implementations of interlocking will be analysed using the example of a simple railway junction where a single bi-directional line diverts to the left. Therefore, there will be a turnout (points) that requires changing its position to set the right route for a train. Also, some kind of indication to the train driver will be required to let the driver know there is no train coming from the opposite direction and the route has been prepared for the train.

Figure 2 shows four possibilities for a train to travel through that railway junction: Main to Normal, Main to Reverse, Normal to Main and Reverse to Main. The points,
therefore, have to be positioned Normal for the movements M→N or N→M and in Reverse when the train is travelling M→R or R→M.

In various applications the points are driven manually with the help of a mechanical mechanism or electrically by means of a points machine.

Where no colliding movements are identified and the right route is prepared for a train, the train driver is authorised to travel through the railway junction with one of the following indicators: flagman, operator's key, semaphore or colour light signal, depending on signalling application.

These four indicators within detailed processes will be used further down when categorising the main types of interlocking system necessary to secure movement on the railway junction presented on Figure 4.

5. Implementation of interlocking on railway junction

This Chapter elaborates on currently implemented interlocking and signalling on railway junctions, categorises the interlocking and defines interlocking processes for those implementations.

There can be three main types of interlocking and signalling systems distinguished in the railway signalling industry that have to be considered when analysing operational conditions on railway junctions. The types are as follows:

- Manual (human) interlocking
- Mechanical interlocking (Mechanical points and Mechanical points and semaphores-described above)
- Electrically powered interlocking (Relay interlocking and Computer based interlocking - CBI).

5.1. Manual (human) interlocking

Since 1804 the first high pressure steam locomotive hauled train has been publicly demonstrated in Merthyr Tydfil (the UK). The steam era has revolutionised the railways, however, it brought new problems for the public. The first passenger train death has been widely reported since September 1830. William Huskisson was killed by Stephenson's Rocket at the opening of the Liverpool and Manchester Railway.

Since that death, the need for signalling became apparent. The first railway signalling system was recorded in 1832. At the beginning it was very simple but not trivial however. The signalling logic relied on a human that signalled the train with a green flag for a proceed signal and red for the stop aspect. An artistic impression of a flagman that has a red flag is reflected on Figure 6.
Figure 6 A model of a flagman

On the drawing it can be observed that the points are equipped with a hand operated lever which is connected to the points blades (connection and points blades not shown). Also, the flagman keeps a red flag up so that the train is not allowed to proceed. He is also coming to the points probably to change their position. The layout of those points cannot be seen, so it is not defined in which position the points are currently set.

A layout that schematically shows a signalling arrangement for a similar situation is reflected on Figure 7.

Figure 7 A points operating lever – points in Normal position

The points on the picture are positioned Normal, which is highlighted on the lever by a black dot next to number one. Number one tells the reader there is only one lever in this arrangement. In the case of a 4 lever ground frame there would be numbers 1, 2, 3 and 4 used. Letters R and N next to the lever show respectively the reverse and normal positions of the lever. Flagman is not shown on the schematic.

Before analysing the manual (human) interlocking algorithm, it is critical to introduce the nomenclature used in the algorithms, so that the reader can follow the idea.

The algorithms are built using traditional states representation (square boxes) that are distinguished using a Greek symbol in a box coloured in yellow, on the right hand side of the state box and conditional steps (rhomb) that are numbered using Roman numbers in a small greyed rhomb on the top of the conditional rhomb. Those Greek symbols and Roman numbers (as shown on Figure 8) are used to help the reader follow the algorithms logic and practical implementation.
Returning to the discussion on Manual (human) interlocking, technically the lever is operated by a signalman. The signalman is also equipped with green and red flags. When required to change the position of the points from Normal to Reverse, the signalman raises the red flag to stop the train, then she/he operates the lever to change the points position. If the points are in the correct position the signalman will raise the green flag to give the authority for the train to proceed.

The algorithm that shows the interlocking process for this signalling arrangement is reflected on Figure 9.
Figure 9 A manual (human) interlocking algorithm

The very first step in the process (state $\alpha$) is to check what authority is given to the train. This is conducted by questioning if the flagman raises the red flag to stop any train approaching the junction (conditional step I). If the red flag is not up, route setting cannot be commenced and the algorithm stays in the same state $\alpha$, otherwise the algorithm enters a points position check (state $\beta$).

There are two conditions in the points position check to be able to proceed to displaying a proceed signal – train not passing the points (conditional step II) and
points in the correct position (conditional step III). Points position is judged by the flagman. In the case that the train is on the set of points the interlocking process goes to the step of displaying a proceed aspect (state $\zeta$) and later to Proceed train (state $\eta$). If the points are required changing their position to Normal or to Reverse the algorithm proceeds to the state Moving points (state $\gamma$) where the flagman is physically moving a lever associated with the points blades. Once the points are moved the flagman judges if the movement is finalised (conditional step IV) and if the points are locked properly (conditional step V). If there is a problem the algorithm enters a state of Points movement system fault (state $\delta$) and the flagman searches for any technical problems. Once the technical problems are resolved the flagman shall start the interlocking procedure again from the beginning (state $\epsilon$).

When the points are positioned as required the flagman decides to display a proceed signal (state $\zeta$). The proceed signal is given by raising a green flag up replacing the red flag. Obviously, the interlocking process must account for any faults related to displaying the green flag (conditional step X). It could be as simple as the flag is absent (state $\kappa$) because the flagman didn’t check the bag for flags before going to site. Once the flag is in place the fault is obviously removed (conditional step XI); however, the flagman shall start the interlocking process from the very first step again (state $\lambda$ and then straight after state $\alpha$).

A train passage (state $\eta$) proceeds only when the green flag is properly displayed to the train driver.

Train passage is observed by the flagman. Once the train passed the railway junction (conditional step VIII) a process of route preparation can be initialised again (state $\theta$). It could happen immediately after if there is no train approaching the junction but it can take a few days before the next train passes that railway junction. So, once the flagman is in position there is a check for approaching trains (conditional step IX) and once again the interlocking process is followed (state $\iota$ and then straight after state $\alpha$).

5.2. Mechanical interlocking

Through the time of improving rail transport, signalling became more and more sophisticated, however, its basic rule remains – allow safe train operations while meeting capacity demands. After flagmen, signalling progressed to the mechanical era with points mechanisms and semaphores mechanically controlled, initially from a ground frame allowing basic operation within the combination semaphore-points and finally from a signal box by means of levers. In this application signalling introduced for the first time the term interlocking which is "an arrangement of signals and signal appliances so interconnected that their movements must succeed each other in proper sequence." [1] It wasn’t actually signals; they were semaphores displaying a signal, one at the time. The signal appliances were mechanical points operated manually from a ground frame. The interconnection of the points and signals was designed in the ground frame and its operation was allowed only when unlocked by a key inserted into ground frame’s lock mechanism.
This mechanical type of interlocking allows capacity of one train per 30-50 minutes depends on track arrangement, due to the fact that the train's route cannot be preselected and levers have to be manually operated. The life cycle of mechanical signalling is impressive. According to Mike Knutton (Senior Editorial Consultant) an average life for a mechanical locking frame in the UK is 75 years. [54]

There are two types of mechanical interlocking that can be clearly distinguished: Mechanical points and Mechanical points and semaphores.

5.2.1. Mechanical points

For mechanical points interlocking the railway junction layout on Figure 2 is equipped with a 2 lever ground frame that is locked by an operator's lock. 2 LEVER GROUND FRAME is a name of the ground frame derived from railway literature. [6]

The operator's lock is a simple locking mechanism that is released by inserting and turning an operator's key. Once the mechanism is unlocked the operator's key stays in showing that the operator's lock is unlocked. To lock the mechanism, the operator's key must be turned back and removed from the lock. A layout that shows this signalling arrangement is reflected on Figure 10. Points are installed with a points indicator to show the train driver which way the points are currently positioned (Normal as shown on Figure 10 or Reverse).

![Figure 10 Signalling arrangement for mechanical points interlocking](image)

The 2 lever ground frame can be operated by a signalman or a train driver. In the first case the rule is similar to the manual (human) interlocking described above.

The signalman equipped with flags raises a red flag if the approaching train needs to be stopped to change the points position. The signalman is this time additionally equipped with a key to release the operator's lock. The lock provides a higher level of security compared with the previous interlocking. Once the operator's lock frees up the 2 lever ground frame, the signalman can unlock the points using one of the ground frame levers (the points lock is to secure the points position when passed by a train) and then operate the second lever, changing the points position. The mechanism automatically locks the points in that position without the necessity to move the locking lever. Then the signalman turns the key of the operator's lock and gives authority to the train to travel through the junction.
The signalman’s function can be performed by the train driver, however, an additional level of security is required (for example, authority to proceed given from a control centre to the train driver to go through the junction to the next section).

Otherwise, the train proceeds without stopping.

This type of interlocking is very sustainable and is still commonly used in for example, the countryside of New South Wales (Australia). However, the system has been enhanced with modern technology for train management using GPS tracking. GPS tracking is applicable only for railway lines with single track. For modern double, triple and more track arrangements, more sophisticated signalling arrangement is desired.

Let’s analyse the interlocking process for this type of interlocking that is reflected on Figure 11.

Starting from the top (state $\alpha$), the first condition is checking the train authority (conditional step I). If the train is not authorised to proceed the interlocking process goes to its checking points position state (state $\beta$). It could be that there is still a train passage (conditional step II). If this is the case the algorithm enters Proceed train state (state $\nu$), otherwise it searches for correct points position (conditional step III).

When it is necessary to change the points position an operator’s key must be inserted into the operator’s lock and turned to release a lever (state $\gamma$). For the example on Figure 10, the operator’s key unlocks ground frame release lever 1.

There might be some problems in unlocking the lever (conditional step X). For example the operator’s key is not suitable for the operator’s lock (conditional step IV). That would be actually a very critical signalling system fault. Another example would be that the key cannot be inserted due to dirty operator’s lock mechanism (conditional step IV). In all those cases the algorithm enters Operator’s key system fault state (state $\delta$) and returns to the initial state (state $\alpha$) when the situation is rectified.

Once lever 1 is released (conditional step XI), it is moved (state $\iota$) to the opposite position releasing lever 2 (conditional step XII) and allowing for points position change (state $\kappa$). Also, in the case of any problems with lever 1 or/and lever 2 a ground frame fault state is introduced in the interlocking process (state $\zeta$). Analogically to an operator’s key fault the system returns to its initial state (state $\eta$ and then straight after state $\alpha$) when the problem is solved (conditional step VIII).
In the case of correct operation lever 2 is moved to the end changing the points position as required (conditional step XIII). The operator's key can be now turned and removed (state $\lambda$). Again, in the case of any technical problems (conditional
steps XIII and XV or steps XIV and XVI) the algorithm enters Operator's key system fault state (state $\delta$) and returns to the initial state when the fault is removed (conditional step VIII).

Once the position change is finalised the interlocking process goes to the state of preparing the route for the approaching train (state $\xi$) and once all checks for points position are conducted (conditional step XIX) an authority is given to the train (state $\mu$). In the case of the signalling arrangement on Figure 10, it will be the points indicator showing points in the right position and giving the authority to proceed. If a train management system with GPS tracking is built within this type of interlocking it could a radio communication authority given by a control centre (conditional step XVII).

Once the authority is given the train passes the railway junction (state $\nu$).

5.2.2. Mechanical points and semaphores

The mechanical points interlocking uses points indicator and train management system (if there is one installed). Mechanical points and semaphores interlocking use similar technology. The only difference is the introduction of semaphores to give a train authority. A signalling arrangement for this type of interlocking for railway junction on Figure 2 is presented on Figure 12.

![Figure 12 Mechanical points and semaphores signalling arrangement](image)

Three semaphores – two single (3 and 4) and one double (1, 2) are designed on the approach to the points 5. The double signal needs to be implemented due to operational requirements. The train driver needs to be informed if the train travels Normal or Reverse on the junction.

In this case, the 5 lever ground frame's levers are connected to the points and to the semaphores. The ground frame also contains a locking mechanism that provides additional protection preventing unwanted lever operations from happening. The 5 lever ground frame is usually built into a housing that secures access to operate the levers.
This arrangement influences application of 5 lever ground frame that is located close to the track. The semaphores as well as points are mechanically connected (set of rodding or/and wires) to the levers of the ground frames.

The ground frame has a designed mechanical locking mechanism that allows only safe operation of the equipment and trains.

In the main state, the semaphores are in the horizontal position and any train approaching the junction is obliged by railway principles to stop.

The signalman, once in the housing, operates the lever(s) as required. For example, if the train stops at semaphore 4 and the points are in the normal position, the signalman needs to operate lever 5 first and then lever 4 to give the train driver authority to proceed.

A drawing that has been adapted from [48] shows the locking mechanism for the arrangement presented on Figure 13.

![Figure 13 Locking mechanism for 5 lever ground frame](image)

As a second example that includes a switch, consider the junction shown on Figure 12. The distant signals and the facing-point lock are not shown, but they would normally be present. The distant signal would have only one arm, and would be cleared only when the straight-through route was set. Lever 1 is pulled for a straight-through movement and lever 2 for a movement to the branch. Only one signal arm may be lowered at a time. In particular, arms 1 and 2 must not be simultaneously lowered. Arms 1 and 3 may be lowered only when lever 5 is normal, arms 2 and 4 only when lever 5 is reversed [48].

<table>
<thead>
<tr>
<th>Lever</th>
<th>Locks lever</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5, 2, 3, 4</td>
</tr>
<tr>
<td>2</td>
<td>5, 3, 4</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 1 Locking sheet for 5 lever ground frame

In Table 1 a locking sheet for this interlocking is shown. This has been adopted from [48]. A bolded, underscored number means that the lever is reversed. The sheet
may be read: lever 1 reversed locks levers 2, 3, 4 and 5 normal. Lever 2 reversed locks levers 3, 4 normal and lever 5 reversed. Lever 3 reversed locks lever 5 normal, and lever 4 reversed locks lever 5 reversed. It has applied the above three rules in constructing this locking sheet. The locking sheet is realized by the interlocking in the previous diagram, as can easily be checked. Since there is no conditional locking, the "when" column is empty [48].

An interlocking process for the junction arranged as described above is more sophisticated than those previously described. Allowing the reader to follow the algorithm steps for mechanical points and semaphores interlocking is divided into the following parts:

- unlocking ground frame (Figure 14)
- checking points position (Figure 15)
- points position change, aspect display and train passage for Normal points position (Figure 16)
- points position change, aspect display and train passage for Reverse points position (Figure 17).

Figure 14 Unlocking ground frame
It has to be noted that in this interlocking a signalman is required to conduct control operations of the interlocking. In particular the signalman is responsible for operating the levers and checking the situation on track. The second function could be enhanced by some kind of tracking; however, the tracking is excluded from the interlocking algorithm employing the signalman to conduct the task.

Similar to the previously described algorithms, the mechanical points and semaphores interlocking process begins with checking train proceed authority (state $\alpha$). The very first step of the process is to confirm that all arms of the semaphores are in horizontal positions (conditional step I). In the case that the position of arms is different to that expected the algorithm detects any semaphores system fault (conditional step II) and enters the state (state $\gamma$). If the semaphores are repaired, it means the semaphore system fault has been removed (conditional step III) and the algorithm performing all checks again (state $\delta$) is now back in the initial state (state $\alpha$) waiting on finalising the previous train control operation.

![Figure 15 Checking points position](image)

Once the semaphores are showing stop aspects (conditional step I), the mechanical interlocking should allow lever 5 to be unlocked (state $\beta$) unless it experiences some technical issues (conditional step IV) that can be detected in this step and resolved in the state lever 5 system fault (state $\zeta$). When the problem is removed (conditional step VI), the algorithm performs all checks again (state $\eta$ and state $\alpha$) returning to the state unlock lever 5 (state $\beta$).

A signalman visually checks the points position (state $\epsilon$) and the algorithm goes to the checking points position part (Figure 15).

When the signalman confirms the absence of train on the points (conditional step VII), it needs to be confirmed which route for the train is being set (conditional steps VIII and IX). There are two possible choices – route $M\leftrightarrow N$ (conditional step VIII) or route $M\leftrightarrow R$ (conditional step IX). If the points for route $M\leftrightarrow N$ are in the reverse position (conditional step XI), the system requires a points position change (state $\iota$).
The signalman changes the position of lever 5 (state \( \iota \)) that moves the points to the normal position. Similar for the other route M\( \leftrightarrow \)R, if the points are in the normal position (state \( \theta \)), lever 5 shall be operated to move the points to the reverse position.

Figure 16 shows points position change, aspect display and train passage when setting routes M\( \leftrightarrow \)R.

![Flowchart diagram](image)

The first check of this portion of the algorithm is to identify if the points are in the correct position post changing their position (conditional step XII). The algorithm enters points movement system fault in the case of points or lever failure (conditional step XIII), otherwise the signalman checks which semaphore lever to...
pull to display the correct proceed aspect (conditional steps XVII and XXI). If this is a route S2→R (conditional step XVII), the signalman pulls lever 2 (state $\xi$). Lever 4 is pulled (state $\varsigma$) when the train is approaching from semaphore S4 (route S4→M) (conditional step XXI).

In the next step the signalman checks if the semaphore displays a proceed aspect (conditional steps XVIII and XV or XXII and XXIV), if not the system is in the state of failure for semaphore 2 (state $\mu$) or semaphore 4 (state $\tau$). Otherwise, the train movement is authorised (state $\omega$ for semaphore 2 and state $\sigma$ for semaphore 4) and the train can proceed accordingly.
Then interlocking process waits until the train has left the railway junction (conditional step XIX or XXIII). Once this is achieved the signalman can start preparing another route (state $\pi$), obviously if there is a train approaching (conditional step XX). Finally the algorithm returns to the initial state (state $\alpha$) after performing all checks (state $\rho$).

Figure 17 illustrates a similar scenario for routes $M \leftrightarrow N$. The points in this case require the normal position (conditional step XXVI) to be able to display proceed aspect on one of those two semaphores $S_1$ (state $\omega$) or $S_3$ (state $\upsilon$).

An interesting element of the algorithm is that after the train left the junction (conditional step XXXI), the interlocking process goes to one common state that is preparing a route for an approaching train (state $\pi$ on Figure 16) where all semaphores are being set to the stop train position.

5.3. Electrically powered interlocking (Relay interlocking and Computer based interlocking - CBI)

An electro-mechanical locking device was invented in 1871. The basic safety idea is that by operating such a device, the signaller will produce a non-reversible locking in his own signalbox that can only be released by either operating a corresponding device in another signalbox or by action of the passing train [47]. That type of interlocking provided good safety solution; rail capacity however remains similar to mechanical interlocking.

Then a need for rail capacity and development of electricity pushed signalling to a next level. The relay interlocking era commenced in 1929. The signalling infrastructure in this type of signalling system contains more elements. Train authority is displayed to train drivers on colour light signals. Points are operated electrically by a remote interlocking system. In the interlocking system, trains are tracked by means of train detection units.

Since the late 1980s, modern interlocking has been introduced. They are known as computer based interlocking (CBI). They have been implemented in many different configurations always taking into consideration the latest computer developments. The earliest CBIs downsize the signalling rooms quite significantly. Development of those systems sees the interlocking being boxed in a microprocessor unit that size is as small as H: 200mm, W: 50mm and D: 200mm. The relay system logic implemented in hardware takes the space of one big bedroom [6].

Both types relay and computer based interlocking will be further analysed as electrically powered interlocking.

Electrically powered interlocking uses three main trackside components that directly impact or are impacted by train operation. Those elements are also power operated. They are the following: colour light signal that displays aspects visible to the train...
driver, points machine that changes points position (reverse or normal) and train detection unit that returns information about the absence of train to electrically powered interlocking. Other equipment like location case, power equipment room, signalling equipment room and communication equipment room are a relevant part of the signalling system; however, they indirectly impact on train operation. They are responsible for the correct operation of the system, being an interface between the trackside equipment and the interlocking.

The railway junction from Figure 2 has been signalled with colour light signals, points machine and train detection units. A layout for electrically powered interlocking is shown on Figure 18.

In this particular scenario, the control centre contains a control system and telecommunication equipment able to communicate bi-directionally with a signalling system that is located in the SER building. The PER building has only equipment needed to power the signalling and telecommunication equipment located in the SER, CER, location cases, colour light signals, points machine and train detection units. There is no telecommunication equipment in the location cases. The interlocking as well as some train detection equipment is located in the SER building.

![Figure 18 Layout for electrically powered interlocking](image_url)

The situation on the railway junction is controlled from a remote Control Centre. A signalman is able to change the points position and authorize a train requesting the task from a computer panel or electrical panel depending on the control system technology. The request is sent to the railway interlocking that controls colour lights and points machines. Railway interlocking decisions rely on its logic and inputs from colour light signals, points and train detection units.

As mentioned above, there are two types of electrically powered interlocking that can signal the situation presented on Figure 18 – relay interlocking and computer based interlocking.

### 5.3.1. Relay interlocking

Relay interlocking is built from a number of relays. The number depends on the complexity of the signalling layout being interlocked for a specific application. The
types of relays used in the interlocking depend on functions being implemented as well as the infrastructure managers’ rules and relevant national standards. For example, relays used in Germany can be different to relays used in Australia; even relays used in the UK could be different to those used in Australia due to different National Electrical and Safety standards. Also, within one country the relays could differ from installation to installation. However, the common, consistent point is the general rule of relay functioning and its construction (coil and contacts).

![Figure 19 A photo showing part of relay interlocking (source: showing product manufactured by Siemens, former Invensys Rail)](image)

It can be observed on Figure 19 that the Australian railway is using mostly Q relays that are mounted on a rack.

In terms of functionality, usually a single interlocking function is built from a single relay. However, relays made with two coils also exist in railway signalling. They are in one enclosure and effectively create a relay that performs two functions. To simplify, it can be stated that one relay coil performs one interlocking function.

Relay interlocking is designed in such a way that relay coils (functions) and relay contacts are wired in electrical circuits so that the entire interlocking will perform as a system specialised to the signalling layout. Therefore, the interlocking logic in this scenario is implemented by means of relay coils, contacts organised in electrical circuits that is perform functions in a parallel processing mode when contacts allow it to do so.

5.3.2. Computer based interlocking (CBI)

Computer hardware (microprocessor, memory, hard drive, etc and input and output cards) and computer software (firmware, operational system and control program) create CBI interlocking. Interlocking functions are defined in a control program, also interlocking inputs and outputs and its association with the hardware are declared in the control program. The control program in the case of CBI is called interlocking logic.
In the instance of a points machine, the computer interlocking is not capable of providing power to directly control the points machine. Relays are still used to perform this functionality.

![Computer Based Interlocking](image)

Figure 20 Computer Based Interlocking with the opened processing part enclosure (source: showing product manufactured by Siemens, former Invensys Rail)

Figure 20 shows the computer hardware of CBI interlocking. It is different from a normal PC because the hardware must be specialised for safety related applications. Therefore, its construction is specific as well as operational system and firmware that are again different from a PC. However, CBI computers like PCs process information sequentially reading and executing instructions step by step in clock cycles.

The interlocking logic is kept in a microprocessor module. This is a list of instructions predesigned specifically for a signalling layout and rules of operation (defined in control tables), checked, tested and compiled that can be performed by the interlocking hardware (computer) preventing trains from colliding.

The list of instructions is prepared in graphical (contacts and coil like) or/and text (e.g. instruction if input a=0 and input b=0 then output a=1) forms. The list of instructions can be stored in many files representing for example, definition of variables, inputs collection, internal instructions, and external instructions and outputs instructions. When compiled a solid interlocking logic is created that is executable by interlocking hardware.

Hardware is controlled by firmware. Firmware is delivered in the hardware manufacturing process, is stored in one of the hardware components and can be changed only by the manufacturer. There is no railway signalling data kept in firmware.
5.3.3. Relay and CBI – algorithm

Although Relay and Computer Based (CB) interlocking has technology and implementation differences from signalling design and railway operation perspectives there are many similarities that allow building a common algorithm for those two interlocking types. The equipment used at the trackside in both types of interlocking is practically the same, starting with motorised points and its detection, through colour light signals and finishing on train detection unit. Control panels in control centres are very similar. They can be implemented as electrically operated, wooden made, panels painted to show the signalling layout with small buttons and lights to allow control and indications and they can be computerised with the signalling layout displayed on various screens with graphical, computer, representation for buttons and lights. The operator can control the buttons using a computer mouse.

There could be some cases where mechanical equipment is in use to control the railway through its relay interlocking. It is very unlikely that a mechanical control panel cooperates with a computer interlocking. Even if it was the case, to operate the computer interlocking would be similar to when cooperating with a relay interlocking.

Despite the various technologies designed in for the control panel as well as trackside equipment, the interlocking structure remains the same in all those cases.

The algorithm prepared for relay and CB interlocking corresponds to the signalled railway junction shown on Figure 18.

There are four possible routes for a train:

- from signal S1 toward signal S4 through reverse position of points P1, the route will be symbolled S1→R
- from signal S1 toward signal S3 through normal position of points P1, symbolled S1→N
- from signal S3 toward signal S1 through normal position of points P1, symbolled S3→M
- from signal S4 toward signal S1 through reverse position of points P1, symbolled S4→M.

The routes cannot be set at the same time because it would open the scenario for a train crash. Therefore, they have to be interlocked within each other allowing just one route at a time.

The system also will need to have an option to independently request individual points movement in a case where for example some maintenance work has to be conducted.
The very first step in the interlocking algorithm is to check for any operator request (conditional steps I and II) and detect its kind, then detect which exact situation is being requested. The checking part of the algorithm is presented on Figure 21.

There are two possible types of operator request – points request (conditional step II) and route request (conditional step I).

When the algorithm identifies it is a points request it also detects if this is a Reverse to Normal (R→N) request (conditional step XXXVIII on Figure 22) or Normal to Reverse (N→R) and then initialises the required points request (conditional step II).

In the case of a route request it is identified which of the listed above four routes are requested (conditional steps III, V, VII and IX). Additionally, it is checked whether the requested route is available (conditional steps IIII, VI, VIII and X). Once those checks are completed the algorithm starts a route pre-selection process (states δ, ε, ζ and η).

5.3.3.1. Points request

The points request part of the interlocking algorithm for Normal to Reverse operation is reflected on Figure 22.

A points request is probably the simplest possible request. When initialising a points request more checks is performed. Obviously, the request could be cancelled (conditional step XXXIX), so the algorithm shall account for this situation (state €). If the points request still goes ahead another check is to find out whether a route is being preselected or even locked (conditional step XXXX). Finally, it has to be checked if the points are positioned properly (conditional step XXXXI) before the algorithm gives the command to start the points machine to change the points position (state Ј). The points could be laid for example in the Reverse position while...
the request is from Normal to Reverse. The request is therefore invalid because the points are already in the requested position. Should this occur, the points request will be cancelled (state $S$) in this step checking also for any technical problems with the points (conditional step XXXXII). The technical problems could be related to the points not being detected in either position.

![Diagram of railway junction interlocking algorithm](image)

**Figure 22** A points request part of the railway junction interlocking algorithm

In the process of moving the points there are two important elements – the interlocking looks for detecting points in the requested position (conditional step
and the interlocking looks for any faults (conditional step XXXXV) that might occur when the points are being moved.

Normally, it takes between 3 and 4 seconds to move a set of points (a points condition monitoring chart for Invensys’s points machine M23A powered with 120V DC is reflected on Figure 23), however some points machines require more time to operate, for example where the same machine uses a different motor and is supplied with 24VDC (a chart for this scenario is presented on Figure 24). In this case, it will take more than 10 seconds to finalise the points position change.

![Figure 23](image)

In the case where the points are operating properly and the movement is not finalised the interlocking will wait until the operation is completed. More information on points faults and methods to improve points reliability using condition monitoring can be found in [52][53].

Once the points are detected in the correct position the algorithm will jump to the state of waiting on another request.

![Figure 24](image)
When the control command has been initialised and points are moving incorrectly or not moving at all, the interlocking will detect the situation (conditional step XXXXV) and wait on in this state (state Ь) until the points are repaired (conditional step XXXXVI) and after performing all checks (state Ь) return to the state of checking train proceed authority (state α) waiting on another request.

### 5.3.3.2. Route request

The pre-selection process of a route is analysed on the example of route S1→N reflected on Figure 25.

![Route pre-selection part of interlocking algorithm for the route request for S1→N](image-url)
The route request process is more complicated than just a points request. However, at some point points machine P1 is also involved. The route request process involves all trackside equipment.

It has to be acknowledged that all trackside equipment is vital for the interlocking; however, a colour light signal is the medium to pass information to a train driver. So, the interlocking must always remember to control the railway in such a way that in any unknown, unstable, undefined or intermediate state it has to always display a red aspect on a signal or signals related to that instability.

The very first step of route pre-selection is to search for any request cancellation (conditional step XI). When the route is cancelled this part of the algorithm forces the interlocking to display a red aspect on the signal, in this case signal S1 (state $\theta$). Before cancelling the route, the interlocking looks for any technical problems with the displayed Red aspect (conditional step XXXVII). If a fault is identified the algorithm keeps the interlocking in a Red aspect fault state (state $i$) until the signal is fault free (conditional step XXXVIII). When a red aspect is displayed properly the route is deselected (state $\kappa$) and the algorithm returns to the initial state (state $\alpha$) waiting on another request.

In the next step the interlocking checks if any other conflicting routes are pre-selected (conditional step XII). If yes the requested route is deselected (state $\kappa$) and the interlocking returns to the initial state (state $\alpha$). Otherwise, it will start checking if the signal displays a red aspect (conditional step XIII) and self-check the route pre-selection (conditional step XVI).

Once the route is pre-selected (state $\nu$), the interlocking looks for track sections that form the requested route to be free (not occupied) - (conditional step XVII). By railway interlocking general rules it is prohibited to set a route if at least one track section being part of the route is occupied.

Before commencing route setting it is vital to check once again for any route cancellation that may occur during implementation of a route request (conditional step XVIII). In the case that there is a cancellation, the interlocking again enters the de-selection process described above (the de-selection process starts in state $\theta$). Otherwise, it commences the route setting process.

### 5.3.3.3. Route setting

The route setting algorithm is shown on Figure 26.

In the route setting process, it is essential to check points position (state $\xi$) and move them if the route requires so. For example, if points P1 are detected in the Reverse position (conditional step XIX), the interlocking on Figure 26 requires to change the points position to Normal. If they are currently lying in the Reverse position the algorithm steps to next task of route setting (state $p$). Otherwise, the interlocking searches for problems with the points (conditional step XXI) if the points are not detected in Reverse and later after controlling the points to the Normal position (conditional step XXIII). Once the points problems are rectified (conditional
step XXII), the algorithm returns to its pre-selection state (state $\delta$) after performing all checks (state $\pi$), the reason being that points repair may take some time and the situation on track may change. A repair of extremely complicated points failures may take a few days and in between repair activities train operations can be controlled on site by a flagman (the flagman algorithm is presented on Figure 9).

![Figure 26 Route S1→N - setting process](image)

5.3.3.4. Displaying proceed aspect

Now the algorithm progresses to the most safety critical step. The step is to authorise the train to cross the section of track by displaying a proceed aspect. Details of the step are presented on Figure 27.

Before a proceed aspect is displayed the route must be locked and approach locked (state $\sigma$) with two checks conducted.

Firstly, the interlocking confirms the ability of the signal to display a proceed aspect (conditional step XXVI). When the signal is not able to do so and a technical problem has been detected (conditional step XXVIII) the algorithm enters a state of proceed aspect fault (state $\iota$) and stays in this state until the problem is solved (conditional step XXXIII) then the interlocking requires to perform all checks for the pre-selected route (state $\upsilon$). A more dangerous situation from a train operation
perspective is when the interlocking does not control the signal, if a proceed aspect cannot be displayed and no fault was recognised the algorithm returns to its initial state informing the system about the unrecognised state of the proceed aspect on the signal (state ω).
Figure 27 Displaying proceed aspect for a train on signal S1

Secondly, the algorithm searches for any route cancellation (conditional step XXVII) that is possible at each stage and has to be accounted for in very critical steps of the interlocking process. In the case of route request cancellation the interlocking returns to the initial state (state $\alpha$) through displaying the Red aspect state (state $\theta$) described above in the pre-selection process. Otherwise the interlocking allows a proceed aspect to be displayed on the signal (state $\tau$).

Once the command was given and the trackside equipment processed the request it is expected that the signal provides the train driver with authority to proceed to the next track section. The interlocking checks if the signal has been displayed properly (conditional step XXVIII) progressing to a state of displaying a Red aspect when the signal failed to do so. The interlocking also commences a Red aspect display in the case of route request cancellation (conditional step XXIX).

In the state of displaying a Red aspect after a proceed aspect command has been introduced (state $u$), the algorithm seeks any technical problems with the signal (conditional step XXX) and in the case that no problems are detected the interlocking enters Release approach locking state (state $\psi$). This is a very important state that is strictly related to train operation. The approach locking function keeps the route locked for any train approaching the signal. Once released the function looks back through train detection units occupancy to check if the route can be immediately released (conditional step XXXII). The route is released at certain conditions through a time (state $\omega$). The conditions and the time are defined in control tables specifically designed for the signalling arrangement.

The layout on Figure 18 shows only one section of track in front of signal S1. Therefore, in this example the interlocking looks only at this bit of track for route $S_1 \rightarrow N$, however, in more complicated layouts approach locking can be very complicated.

5.3.3.5. Train passage and route release

The final part of the interlocking process is to look for the train passage and release (state $\delta$) the route, allowing another route request.

Looking at the signalling principles when the first axle of a train crosses a section of track behind a signal, the signal must immediately display a Red aspect. Looking at the Train operated route release of the interlocking algorithm on Figure 28, it can be observed that for route $S_1 \rightarrow N$ the interlocking searches for occupancy of the train detection unit 2T. Immediately after the track 2T (conditional step XXXIII) enters the occupied state the algorithm forces a Red aspect on signal S1 (state $\upsilon$) checking then if the red aspect is properly displayed (conditional step XXXIV). Once the red aspect is properly detected the interlocking waits on train passage and release of all track sections involved in route $S_1 \rightarrow N$ (conditional step XXXV). Unlocking the route and returning to the initial state commences straight after the train detection units confirmed the track sections are not occupied (state $\upsilon$).
5.3.4. Implementation differences

The relay interlocking influences the need to control trains remotely due to the fact that interlocking is now centralised for a quite extensive area and human actions are limited to requesting route pre-selection. The interlocking logic in this case is implemented in circuits that perform specific functions. The interlocking in these circuits is done by relay contacts from relays performing those specific functions.

Relays offer the following advantages:

- low technical risk regarding safety approval
- operational performance that can meet all requirements, and
- an economic life long enough to match the capacity of the industry to maintain and renew installations in the long term. [54]
Analysing the algorithm for Relay and Computer Based interlocking (Section 5.3.3), under implementation in relay technology it has to be noted that many operations within sequential process of the algorithm are conducted by parallel processing of relay operations. For example conditional steps of the algorithm are reacting on inputs from trackside equipment. If a train gets authority to proceed and commences its journey entering the next track section the relay function for the track section immediately informs the system the train is on. Contacts of that relay are in the colour light signal; therefore it reacts to that track section occupancy by displaying a red aspect. Those actions are not waiting on an interlocking process. So, the relay interlocking has two kinds of processing: sequential - interlocking process and parallel interlocking functions implementation. Sequential processing of relay interlocking is done by implementing a hierarchy of relay circuits. Effectively appropriate arrangement of relay contacts in those circuits provides sequence while relays are concurrently processed.

Also important is the relay interlocking life cycle and capacity. According to Mike Knutton, the average life cycle of an electro-mechanical relay in the UK is 25 years. [54] The relay interlocking allows capacity of one train every 3-5 minutes again depending on track arrangement.

Modern types of interlocking, those installed since the late 1980s, are computer based interlocking (CBI). They have been implemented in many different configurations always taking into consideration the latest computer developments. The earliest CBIs downsize the signalling rooms quite significantly. Development of those systems sees the interlocking being implemented in a microprocessor unit that size is as small as H: 200mm, W: 50mm and D: 200mm while the relay system logic implemented in hardware takes the space of one big bedroom or more. [54]

There are a few reasons why CBI interlocking was introduced to railways in the space previously occupied by relays. They are the following:

- interlocking logic previously implemented in circuits (hardware) is done in a computer program (software) that is run in computer hardware
- computer hardware necessary to implement an interlocking takes much less space than its equivalent in relays
- interlocking can be installed remotely and be transmitted to/from the objects (signal, points machines, etc)
- electronic implementation of interlocking allows digital or software communication with other systems (passenger information system, maintenance system, etc).

Comparing the technology implementation in greater detail, computer based interlocking is processed sequentially in computing processing. Additionally, conditional checks are also implemented in computing processing. Obviously in this type of processing it is required to have some kind of operational system and some firmware. Both elements are also computed in the same process which leads to the interlocking process being much longer. In terms of detailed processing it has been
observed that computers in some interlocking implementation (for complicated stations) are processing slower than an equivalent in relay technology.

The capacity that CBI interlocking provides is similar to what relay interlocking can offer. It has been observed that the CBI logic processing time is generally slower than relay interlocking is.

There are many advantages and disadvantages of computer based interlocking. However, signalling experts are not convinced which interlocking implementation gives more benefits or simply which technology suits better current railway needs. According to Mike Knutton (Senior Editorial Consultant), unforeseen delays in the acceptance process for computer-based interlocking (CBI) in Britain has persuaded at least some experts that relay interlocking technology still has a valid and developing future for controlling line-side signalling. [54]

The unforeseen delays in the acceptance process for CBI can be caused by the following:

- lack of formal methods to describe behaviour of the interlocking
- many different applications of CBI interlocking
- railway expectations to implement more functionality at the same interlocking processing speed
- tools to maintain CBI interlocking are not efficient or there is a lack of such tools
- estimated average life of equipment.

On the other hand some engineers are strongly supporting CBIs. D. Bahr in [45] believes the first types of computer interlocking were more difficult and costly to operate and maintain, however new types of interlocking based on standard components are to be cheaper, more efficient and flexible.

6. Railway junction operational conditions and performance measures

In this Chapter, railway junctions’ operational conditions are introduced and discussed to specify requirements for interlocking on a railway junction. It defines analytical models for the calculation of a railway junction’s requirements including minimum distance, maximum velocity and minimum train travel time for the given track arrangement, thus enabling transport planners to build a train travel chart that graphically describes the required train operations with a special attention to interlocking processing time requirements. It presents the outcomes obtained from the use of the developed methodology in a coal transportation planning task within the framework of one of our most recent railway junction signalling & interlocking coal transport projects in Australia.
The need for railway loops, rail spurs and railway stations is determined by operational conditions. Further in this thesis, the discussion on track arrangement will be constrained to a single, bi-directional railway line with passing loops and a spur only (as reflected on Figure 4) to determine operational conditions on a railway junction.

Railway track, passing loop, rail spur and railway station are generally needed for train operations.

A train is a vehicle that travels on the railway track to transport goods or/and passengers. There are three major categories of trains – freight, passenger and others (Figure 29). A freight train is a train that contains one or more locomotives and wagons that are constructed in a way to be able to transport goods, minerals, chemicals and liquids. Passenger trains are designed to transport humans on a suburban, regional and country distance. They can be set similar to freight trains, a locomotive with passenger wagons replacing the freight wagons. It also can be a train that is effectively one long unit, used specially on suburban rail networks. Others can be a single locomotive, a maintenance vehicle, a car on rail wheels (hi-rail vehicle) and any other vehicle that travels on railway track.

![An example of a single locomotive](image)

![An example of passenger train](image)

![An example of freight train](image)

Figure 29 Example of trains in three major categories

Let’s analyse the potential train travels on the track arrangement presented on Figure 4.

Figure 30 shows the potential start and end points of possible train trips.

On the picture, the train was schematically shown as a single locomotive to simplify the picture. However, it could be passenger train or/and freight train as well.
On Figure 30, there are six trains (in train positions 1 to 6) that show four types of train travel through the railway junction:

- from the passing loop 1, the train in position 2 will travel M->R on the railway junction to the rail spur (train position 3)

- from the rail spur, the train in position 3 will go through the railway junction R->M to complete its mission at the passing loop 1, train position 1

- from the passing loop 1, the train in position 2 will travel M->N on the railway junction to the passing loop 2 (train position 6)

- from the passing loop 2, the train in position 5 will go through the railway junction N->M to complete its mission at the passing loop 1, train position 1.

Considering the train as the track arrangement influencer, the train’s length automatically comes to mind. Currently, in the rail industry rail operators very commonly use freight trains that are 1.5km long. The near future will see trains 2km long as this is a very effective way of increasing mineral transport capacity on current infrastructure that requires little modification. In a majority of cases, only railway loops and rail spurs have to be extended to be able to accommodate longer trains on an existing track arrangement.

When the train accelerates to a certain speed then stops, this train operation needs a certain distance as well. Depending on the train design and the train weight it stops in a distance. The distance that a train travels from the moment of applying the train brakes till its full stop is defined as braking distance and it considers the train’s maximum weight, the locomotive characteristics and the train design. In the train design, there is a subcategory of trains that may impact the details of track arrangement and may influence the need to build additional infrastructure. The locomotive can be propelled by a steam engine (very rare these days, purely available on tourist lines), by an electrical motor or by a diesel engine. As the design of the locomotives in those cases is different, the train braking characteristics will be different and needs to be taken into consideration in the operational conditions. The
worse possible scenario (the longest possible braking distance) should be considered when designing the track arrangement.

Acceleration has been mentioned above. The train will accelerate to a speed. The speed depends on track design that defines the maximum speed allowed for a section of track. That is influenced by terrain conditions. It could be a level section of track or a train path can descend or rise at various angles. It is crucial to note that a train travelling one way descends on that path increasing its speed while travelling in the opposite direction on the same bit of track the train will decrease its speed as it has to climb the hill.

6.1. Track design and minimum distances

The following minimum distances can be distinguished within the rail arrangement on Figure 30:

- passing loop 1 minimum length \([s_{pl1_{-}min}]\)
- railway junction minimum length \([s_{j_{-}min}]\)
- passing loop 2 minimum length \([s_{pl2_{-}min}]\)
- rail spur minimum length \([s_{rs_{-}min}]\)
- section’s minimum length between passing loop 1 and railway junction \([s_{s1_{-}min}]\)
- section’s minimum length between passing loop 2 and railway junction \([s_{s2_{-}min}]\)
- section’s minimum length between rail spur and railway junction \([s_{s3_{-}min}]\).

![Figure 31 Minimum distances as defined in track design on the single track arrangement](image-url)
Now, let's reintroduce Figure 31 to show types of railway signalling implemented.

### 6.1.1. Manual (human) interlocking

Manual (human) interlocking as shown on Figure 7 has been rolled out on the rail arrangement mentioned above and the results are show on Figure 32.

![Figure 32 Railway junction within rail arrangement signalled with manual (human) interlocking](image)

### 6.1.2. Mechanical interlocking

#### 6.1.2.1. Mechanical points

Consistently following the implementation above and taking into consideration Figure 10, mechanical points interlocking implemented on a railway junction within the rail arrangement is depicted on Figure 33 below.
6.1.2.2. Mechanical points and semaphores

The railway junction signalled with mechanical points and semaphores has been previously described in section 5.2.2. The rail arrangement with implemented mechanical points and semaphores is shown on Figure 34 below.

M Main
N Normal
R Reverse

Figure 33 Railway junction within rail arrangement signalled with mechanical points

Figure 34 Railway junction within rail arrangement signalled with mechanical points and semaphores
6.1.3. Electrically powered interlocking (Relay interlocking and Computer based interlocking - CBI)

Finally, the electrically powered interlocking has been implemented on the railway junction within the rail arrangement below (Figure 35).

It is now time to analyse in detail passing loop 1 minimum length \[ s_{pl1_{\text{min}}} \], railway junction minimum length \[ s_{rj_{\text{min}}} \], passing loop 2 minimum length \[ s_{pl2_{\text{min}}} \], rail spur minimum length \[ s_{rs_{\text{min}}} \], section’s minimum length between passing loop 1 and the railway junction \[ s_{s1_{\text{min}}} \], section’s minimum length between passing loop 2 and railway junction \[ s_{s2_{\text{min}}} \] and the section’s minimum length between the rail spur and the railway junction \[ s_{s3_{\text{min}}} \] as consistently shown on Figure 31 to Figure 34.

The track design shall consider braking distances \[ s_{bd} \] with maximum speed, maximum train length \[ s_{t_{\text{max}}} \] and minimum clearance on railway junction \[ s_{c_{\text{min}}} \] to determine the minimum distances required to conduct train operations.

Taking \[ s_{pl1_{\text{min}}} \] as an example, there will be a braking distance component \[ s_{bd} \] included (to stop the train at the stop aspect and to secure a potential SPAD – Signal Passed At Danger - in case the train overran) along with maximum train length \[ s_{t_{\text{max}}} \] and minimum clearance on railway junction \[ s_{c_{\text{min}}} \]. The example has been detailed on Figure 36.
Passing loop 1

Train position 1
Train position 2

Passing loop 1

Figure 36 A breakdown of passing loop 1 minimum length

On the drawing \([s_{bd1}, s_{bd2}, s_{bd3}, s_{bd20}, s_{bd21}, s_{bd22}]\), \([s_{t_{\text{max}}}]\) and \([s_{c_{\text{min}}}]\) are shown separately for Train position 1 (in blue) and Train position 2 (in green). Those illustrate the actual situation in the trains’ travels.

To understand the breakdown it is desired to introduce a signalling system on the passing loop 1. Passing loop 1 has been signalled with mechanical points and semaphores interlocking (for a start) and the result is shown in the layout on Figure 37.

Figure 37 Passing loop 1 signalled with mechanical points and semaphores interlocking

Let’s analyse the travel of train position 1 first (in blue). Imaging the train commences its movement from semaphore \(S_{\text{Down1}}\) toward \(S_{\text{Down3}}\), first there is a braking distance \([s_{bd20}]\) that secures overpassing semaphore \(S_{\text{Down1}}\) or \(S_{\text{Down2}}\), further down, \([s_{c_{\text{min2}}}]\) that is necessary to keep the points \(5[\text{Up}]\) and the railway junction clear. The clearance is necessary to avoid a collision of the end of train position 1.
with another train travelling over that railway junction when the train position 1 is maximum length and it stops at semaphore $S_{\text{Down3}}$.

The next distance on the way is the maximum train length $[s_{t_{\text{max}}}]$ and braking distance $[s_{\text{bd21}}]$ that allows the train to safely stop from its maximum speed to stop at semaphore $S_{\text{Down3}}$ and one more braking distance $[s_{\text{bd22}}]$ that secures overpassing semaphore $S_{\text{Down3}}$ (potential SPAD at $S_{\text{Down3}}$). Finally, there is a clearance of points $5[\text{Down}]$ required and therefore minimum clearance on railway junction distance $[s_{c_{\text{min1}}}]$ is shown at the end of train position 1 movement.

Train position 2 travelling to semaphore $S_{\text{Up1}}$ needs a braking distance to secure overpassing. It has been highlighted as $[s_{\text{bd1}}]$ on Figure 37. Then mentioned above clearance of points $5[\text{Down}]$ that is $[s_{c_{\text{min1}}}]$, maximum train length $[s_{t_{\text{max}}}]$, braking distance $[s_{\text{bd2}}]$ to stop the train position 1 at semaphore $S_{\text{Up4}}$ and braking distance for potential SPAD at $S_{\text{Up4}}$ $[s_{\text{bd3}}]$. The last distance to consider in the movement of train position 1 is minimum clearance on the railway junction $[s_{c_{\text{min2}}}]$ mentioned before.

The analysis of train position 1 and train position 2 travels gives a full breakdown of the minimum length of passing loop 1 that can be mathematically described. An equation that calculates the minimum length of passing loop 1 is presented on (1) or (2).

\[
s_{\text{pl1}_{\text{min}}} = s_{\text{bd1}} + s_{c_{\text{min1}}} + s_{t_{\text{max}}} + s_{\text{bd2}} + s_{\text{bd3}} + s_{c_{\text{min2}}} + s_{\text{bd20}}
\]

\[
s_{\text{pl1}_{\text{min}}} = s_{\text{bd1}} + s_{c_{\text{min1}}} + s_{t_{\text{max}}} + s_{\text{bd22}} + s_{\text{bd6}} + s_{c_{\text{min2}}} + s_{\text{bd21}}
\]

The braking distances are different because they depend on the maximum train speed for the section of track as well as the terrain. Therefore, both $[s_{\text{pl1}_{\text{min}}}]$ as reflected on equation (1) and (2) shall be calculated and the higher value of $[s_{\text{pl1}_{\text{min}}}]$ shall be selected for further discussion.

Let’s see if the same distance defined within $[s_{\text{pl1}_{\text{min}}}]$ can be applicable to passing loop 1 signalled with manual (human) interlocking, mechanical interlocking - mechanical points and electrically powered interlocking.

Looking at Figure 38 and Figure 39, there is no clear point where the train stops at the railway junctions within passing loop 1. The signalman with flags operating the lever will stand close to the lever. There is no signage for the train to show where exactly is the train stopping point, however, the train driver knows the train shall be stopped in braking distance from the points as written in railway operational procedures (train driver manual).
Therefore, in both cases there should be braking distances considered towards stopping the train at the railway junction. Also the railway junction clearance within the passing loop needs to be taken into consideration to clear passage of a train through passing loop 1 railway junction in the case of another train stopped at the junction as well.

Electrically powered interlocking practically follows the points and semaphores interlocking rules. The colour light signals are positioned in the places the semaphores are in the points and semaphores interlocking. Even though the signalling technology implemented on passing loop 1 differs and also the way the signalling systems are operated is different, the distances defined in equations (1) and (2) remains unchanged in electrically powered interlocking as reflected on Figure 40 below.
Figure 40 Passing loop 1 signalled with electrically powered interlocking

Having analysed the passing loop 1 minimum distances, it can be seen that all the distances from equations (1) and (2) have to be considered irrespective of which type of interlocking is implemented on passing loop 1. Therefore, equations (1) and (2) are applicable for manual (human) interlocking, mechanical interlocking (mechanical points and mechanical points and semaphores - described above) and electrically powered interlocking (Relay interlocking and computer based interlocking - CBI).

Let’s consistently analyse passing loop 2. Following the example of $s_{pl1_{min}}$, passing loop 2 as reflected on Figure 31 is configured in a very similar way to passing loop 1. The schematic of passing loop 2 signalled with mechanical points and semaphores interlocking and the distances highlighted is shown on Figure 41.
Figure 42 Passing loop 2 signalled with manual (human) interlocking

Figure 43 Passing loop 2 signalled with mechanical points interlocking
The same distances as reflected on Figure 41 to Figure 44 (for each type of the railway interlocking) shall be considered when calculating $[s_{pl2\_min}]$.

To calculate the passing loop 2 minimum length $[s_{pl2\_min}]$, the equations (1) and (2) will be modified to reflect the correct measurements.

$$s_{pl2\_min} = s_{bd9} + s_{c\_min} \_5 + s_{r\_max} +$$
$$+ s_{bd10} + s_{bd11} + s_{c\_min} \_6 + s_{bd12}$$

(3)

$$s_{pl2\_min} = s_{bd9} + s_{c\_min} \_5 + s_{r\_max} +$$
$$+ s_{bd14} + s_{bd13} + s_{c\_min} \_6 + s_{bd12}$$

(4)

Both $[s_{pl2\_min}]$ shall be calculated and the higher value has to be considered in further analysis.

Continuing the analysis of minimum distances from Figure 31, in the following paragraphs let’s analyse the rail spur minimum length $[s_{rs\_min}]$.

Rail spur minimum length $[s_{rs\_min}]$ needs to be looked at separately. A consistent approach has been applied at the distance breakdown preparation. The results, where mechanical points and semaphores interlocking is implemented, are shown on Figure 45.
Figure 45 Rail spur signalled with mechanical points and semaphores interlocking

There are two train positions illustrated – train position 3 and train position 4. It can be imagined the train in position 3 and the train in position 4 are effectively implementing the same travel, however, it is important to present two train positions to understand how the train travels on the rail spur (for a future practical example).

The train enters the rail spur from semaphore SRs1 and travels ahead through points Rs5 normal direction. There is a braking distance [sb7] associated with that semaphore. Then there is clearance [sc4] required and the train travels around the balloon loop to approach semaphore SRs4. There is maximum train length [st_max] and braking distance [sb15] when the train is stopping at SRs4. There is also braking distance [sb16] allocated behind the semaphore SRs4 in case the semaphore is a SPAD. At the end there is clearance [sc4] that is shown twice for the same train operation, however, this provides a consistent view and allows a full understanding of the situation.

Analysing railway loops, on Figure 46, a rail spur signalled with manual (human) interlocking has been presented.

Figure 46 Rail spur signalled with manual (human) interlocking
The distances in the case of manual (human) interlocking and mechanical points and semaphores interlocking are the same even though there is no sign at which the train shall stop at the railway junction. All distances shall be considered to assure a safe signalling method of securing train operations.

A rail spur signalled with mechanical points interlocking is shown on Figure 47.

![Figure 47 Rail spur signalled with mechanical points interlocking](image)

Figure 47 Rail spur signalled with mechanical points interlocking

This application is very similar to the manual (human) interlocking. The train driver also needs to stop at the railway junction in the distance clear from other train operations. All distances as defined for a rail spur signalled with mechanical points and semaphores interlocking are applicable as reflected on Figure 47.

Figure 48 shows a rail spur signalled with electrically powered interlocking. Colour light signals are positioned like semaphores in the mechanical points and semaphores interlocking. The same minimum distances presented earlier are applicable in the electrically powered interlocking implemented on the railway spur as presented on Figure 48.

![Figure 48 Rail spur signalled with electrically powered interlocking](image)
The equation for rail spur minimum length \([s_{rs\_min}]\) is shown in (5) below.

\[ s_{rs\_min} = s_{bd7} + s_{c\_min\_4} + s_{l\_max} + s_{bd15} + s_{bd16} \]  \hspace{1cm} (5)

Next, the railway junction’s minimum length \([s_{rj\_min}]\) will be analysed. A breakdown of the railway junction’s minimum length \([s_{rj\_min}]\) has been schematically shown on Figure 49. The picture presents a railway junction signalled with mechanical points and semaphores interlocking.

![Figure 49 Railway junction signalled with mechanical points and semaphores interlocking](image)

For a train travelling M-\(\rightarrow\)R or M-\(\rightarrow\)N through the railway junction, the braking distance \([s_{bd5}]\) has to be considered for a potential SPAD at semaphore S1 or S2 and distance for points 5 clearance \([s_{c\_min3}]\). For a train travelling from R-\(\rightarrow\)M, braking distance \([s_{bd123}]\) for a SPAD at semaphore S4 shall be considered and distance for points 5 clearance \([s_{c\_min3}]\). For a train travelling from N-\(\rightarrow\)M, braking distance \([s_{bd18}]\) is allocated and distance for points 5 clearance \([s_{c\_min3}]\).

In the case of manual (human) interlocking, the railway junction signalling layout will look like the one presented on Figure 50.
Figure 50 Railway junction signalled with manual (human) interlocking

Figure 51 presents a railway junction signalled with mechanical points interlocking.

And finally the same railway junction has been signalled with electrically powered interlocking. The results are presented on Figure 52.
Equation (6) below considers the railway junction minimum length for M->R, M->N and N->M train travel, equation (7) defines the breakdown for railway junction minimum length when train travels R->M. Those equations are applicable to all types of railway interlocking as presented on Figure 49 to Figure 52.

\[ s_{ij\_min} = s_{bd5} + s_{c\_min} + s_{bd18} \]  \hspace{1cm} (6)

\[ s_{ij\_min} = s_{bd5} + s_{c\_min} + s_{bd23} \]  \hspace{1cm} (7)

The higher value of \( [s_{ij\_min}] \) shall be implemented as the safer option.

Looking at Figure 31, the outstanding minimum distance to analyse are \( [ss1\_min] \), \( [ss2\_min] \) and \( [ss3\_min] \).

The breakdown of the section’s minimum length between passing loop 1 and railway junction \( [ss1\_min] \) has been presented on Figure 53.
It has been previously mentioned when talking about passing loop 1 and the railway junction that there are braking distances in front of semaphores $S_{\text{Down1}}$ and $S_{\text{Down2}}$ considered in the passing loop minimum length and braking distance in front of semaphore $S_1$ and $S_2$ allocated in the railway junction minimum length.

The train that stops at semaphore $S_1$ and $S_2$ needs braking distance $[s_{bd4}]$ and it has its maximum length $[s_{t_{\text{max}}}]$ that also has to be included in $[s_{s1_{\text{min}}}]$. At the other side, the train that stops at $S_{\text{Down1}}$ and $S_{\text{Down2}}$ needs braking distance $[s_{bd19}]$ and its maximum length is $[s_{t_{\text{max}}}]$.

When considering manual (human) interlocking or mechanical interlocking - mechanical points, the section between passing loop 1 and the railway junction with minimum distances highlighted will look like that presented on Figure 54.

![Figure 54 Rail section between Passing loop 1 and Railway junction signalled with manual (human) interlocking or mechanical points interlocking](image)

Please note in these two types of interlocking, there is a need to provide some safeworking method to authorise a train to leave passing loop 1 or the railway junction. As mentioned previously, only one train is allowed per section. In practice, the signalman at the railway junction authorises the train to proceed through the junction and to the next junction. Sometimes, as part of the authorisation, the section is equipped with block section equipment. As part of authorising a train, the signalman operates the block section equipment to block the authority to let another train from the other side enter the section. In the older systems it used to be a ticket (a piece of paper with written directions for the train driver that was secured in a box. The box could be opened by a metal key carried by the train driver). The ticket was signed by the signalman and given to the train driver together with the key when authorising the train to proceed to the section. In the newer system, there is a computer with the train’s on-board equipment that supports or even gives authority to the train to pass the junction and enter the section in between the passing loop 1 and the railway junction. Irrespective of the section block method, the minimum distances that shall be considered remains for manual (human) interlocking and mechanical points interlocking.

Electrically powered interlocking implemented on the rail section between passing loop 1 and the railway junction is presented on Figure 55.
There can be observed similarities between semaphores and colour light signals. Additionally, there are some train detection units and location cases reflected on Figure 55. The train detection units and location cases have no influence when considering the minimum length between passing loop 1 and the railway junction.

The following equations describe the minimum length between passing loop 1 and the railway junction \( [s_{s1\_min}] \).

\[
\begin{align*}
    s_{s1\_min} &= s_{1\_max} + s_{bd/4} \\
    s_{s1\_min} &= s_{bd/19} + s_{1\_max}
\end{align*}
\]

The train travels on a single line and there is just one train allowed in the section, therefore the higher value from equations (8) and (9) shall be taken into consideration as the section’s minimum length between passing loop 1 and the railway junction \( [s_{s1\_min}] \). Equations (8) and (9) are applicable to all types of defined railway interlocking systems.

Finally referring back to Figure 31, there are two remaining distances: minimum length of section between passing loop 2 and the railway junction \( [s_{s2\_min}] \) and minimum length of section between the rail spur and the railway junction \( [s_{s3\_min}] \).

The distance breakdown of the section’s minimum length between passing loop 2 and the railway junction \( [s_{s2\_min}] \) and the distance breakdown of the section’s minimum length between the rail spur and the railway junction \( [s_{s3\_min}] \), where mechanical points and semaphores interlocking is implemented, have been presented on Figure 56.
The braking distances in front of semaphores S3 and S4 have been considered as part of the railway junction minimum length \( s_{rj \text{min}} \). The braking distance in front of semaphore S_{Rs1} and S_{Rs2} is taken into account in the rail spur minimum length \( s_{rs \text{min}} \) while passing loop 2 minimum length \( s_{pl2 \text{min}} \) includes the braking distance in front of semaphore S_{Up1} and S_{Up2}.

Figure 57 shows the rail section between the railway junction and rail spur & railway junction and passing loop 1 signalled with manual (human) interlocking or mechanical points interlocking. Figure 58 presents the same rail section signalled with electrically powered interlocking. The same distances within \( s_{s2 \text{min}} \) and \( s_{s3 \text{min}} \) are applicable to all types of railway interlocking defined earlier.
Equation (8) and (9) are modified to reflect the minimum length of section between passing loop 2 and railway junction \([s_{s2_{\text{min}}}]\) and minimum length of section between the rail spur and the railway junction \([s_{s3_{\text{min}}}]\). The end result is comparable with the minimum length between passing loop 1 and the railway junction \([s_{s1_{\text{min}}}]\).
The equations for the section’s minimum length between passing loop 2 and the railway junction \([s_{ss2\_min}]\) are as follows:

\[
s_{s2\_min} = s_{i\_max} + s_{bd8} \quad (10)
\]

\[
s_{s2\_min} = s_{bd17} + s_{i\_max} \quad (11)
\]

The equations for the section’s minimum length between the rail spur and the railway junction \([s_{ss3\_min}]\) are presented below.

\[
s_{s3\_min} = s_{i\_max} + s_{bd6} \quad (12)
\]

\[
s_{s3\_min} = s_{bd24} + s_{i\_max} \quad (13)
\]

The higher value of the distance from equations (10) and (11) above shall be considered for \([s_{ss2\_min}]\) and the higher value of the distance from equations (12) and (13) shall be considered for \([s_{ss3\_min}]\).

### 6.2. Minimum train travel time

So far there has been discussion about minimum distances and also very briefly train operations have been mentioned.

#### 6.2.1. Travel distance

Knowing the minimum distances, each train trip within our rail arrangement can be now mathematically defined using the minimum distances. Let's have a look into each of the possible movements as shown on Figure 30 and described in the text below that schematic:

- from the passing loop 1, the train in position 2 will travel \(M->R\) on the railway junction to the rail spur (train position 3)

\[
s_{M->R} = s_{bd3} + s_{i\_min} + s_{bd20} + s_{i\_min} + s_{bd24} + s_{i\_max} + s_{bd15} \quad (14)
\]

- from the rail spur, the train in position 3 will go through the railway junction \(R->M\) to complete its mission at the passing loop 1, train position 1

\[
s_{R->M} = s_{bd16} + s_{i\_min} + s_{bd17} + s_{s3\_min} + s_{i\_min} + s_{bd21} + s_{i\_max} \quad (15)
\]

- from the passing loop 1, the train in position 2 will travel \(M->N\) on the railway junction to the passing loop 2 (train position 6)
10max_5min_9min_2min_5min_1202min_3
bdtc 
sbdcbdNM
ssssss
+++++
++++=>−
(16)

• from the passing loop 2, the train in position 5 will go through the railway junction N->M to complete its mission at the passing loop 1, train position 1.

21max_2min_20min_1min_5min_295min_14
bdtc 
sbdcbdMN
ssssss
+++++
++++=>−
(17)

It would be desired to know what the maximum travel distances are; however, taking into consideration breakdowns defined in equation (1) to (13), any additional distance (for example a loading station on the rail spur that requires to accommodate two train lengths \([s_{\text{max}}]\) instead of one or a level crossing built on the track that requires clearance when the train stops) can be easily added into those equations and equations (14) to (17) will automatically become real distances in those train trips.

6.2.2. Maximum velocity

In section 6.2 of this thesis, there is a discussion about time of train travel. The time is associated with velocity and distance.

The average speed of an object is commonly defined to be the length of the path travelled by an object \(\Delta s\), divided by the time taken \(\Delta t\); i.e.,

\[
\bar{v} = \frac{\Delta s}{\Delta t}
\]  

(18)

\(\Delta s\) in our cases will be \(s_{M->R}, s_{R->M}, s_{M->N}\) and \(s_{N->M}\).

In fact the train is not always in a straight line motion, the track is curved, e.g. travelling through the junction M->R. However, finding time of train operation, it can be simplified that the train travels the straight line motion and therefore, breakdown values of the minimum distances as presented as straight lines.

The track design will provide information about the maximum train speed in certain sections of track. The average maximum speed within sections described by formulas (14)-(17) will be further known as \(\bar{v}_{M->R}\), \(\bar{v}_{R->M}\), \(\bar{v}_{M->N}\) and \(\bar{v}_{N->M}\).

For example \(\bar{v}_{M->R}\) will be calculated in the following way:

\[
\bar{v}_{M->R} = \frac{v_{\text{max}} + v_{\text{max}} + v_{\text{max}} + v_{\text{max}} + v_{\text{max}}}{5}
\]  

(19)

Breaking down further, for example \(v_{\text{max}}\) and applying equation (6), the average maximum speed on the railway junction will be as follows:
Finally, having defined the distances and the maximum average speed, applying equation (18), the minimum train travel time on the rail arrangement presented on Figure 30 can be calculated using the following formulas:

- Train travel from the passing loop 1, train in position 2 will travel M->R on the railway junction to the rail spur (train position 3)

\[
\Delta t_{M->R} = \frac{\Delta s_{bd3}}{v_{bd3\_max}} + \frac{\Delta s_{c\_min2}}{v_{c\_max2}} + \frac{\Delta s_{bd20}}{v_{bd20\_max}} + \frac{\Delta s_{s1\_min}}{v_{s1\_max}} + \frac{\Delta s_{ij\_min}}{v_{ij\_max}}
\]

(21)

- Train travel from the rail spur, train in position 3 will go through the railway junction R->M to complete its mission at the passing loop 1, train position 1

\[
\Delta t_{R->M} = \frac{\Delta s_{bd16}}{v_{bd16\_max}} + \frac{\Delta s_{c\_min4}}{v_{c\_max4}} + \frac{\Delta s_{bd7}}{v_{bd7\_max}} + \frac{\Delta s_{s3\_min}}{v_{s3\_max}} + \frac{\Delta s_{ij\_min}}{v_{ij\_max}}
\]

(22)

- Train travel from the passing loop 1, train in position 2 will travel M->N on the railway junction to the passing loop 2 (train position 6)

\[
\Delta t_{M->N} = \frac{\Delta s_{bd3}}{v_{bd3\_max}} + \frac{\Delta s_{c\_min2}}{v_{c\_max2}} + \frac{\Delta s_{bd20}}{v_{bd20\_max}} + \frac{\Delta s_{s1\_min}}{v_{s1\_max}} + \frac{\Delta s_{ij\_min}}{v_{ij\_max}} + \frac{\Delta s_{bd9}}{v_{bd9\_max}} + \frac{\Delta s_{c\_min5}}{v_{c\_max5}} + \frac{\Delta s_{s2\_min}}{v_{s2\_max}} + \frac{\Delta s_{bd10}}{v_{bd10\_max}}
\]

(23)

- Train travel from the passing loop 2, train in position 5 will go through the railway junction N->M to complete its mission at the passing loop 1, train position 1

\[
\Delta t_{N->M} = \frac{\Delta s_{bd14}}{v_{bd14\_max}} + \frac{\Delta s_{c\_min5}}{v_{c\_max5}} + \frac{\Delta s_{bd9}}{v_{bd9\_max}} + \frac{\Delta s_{s2\_min}}{v_{s2\_max}} + \frac{\Delta s_{ij\_min}}{v_{ij\_max}}
\]

(24)

The formulas (21)-(24) are focused on defining the minimum travel time. The times are graphically presented on Figure 59 in a form of a train describer chart.
The chart has been constructed in such a way that on the Y axis of the chart, there are trains in positions 1, 2, 3, 5 and 6 shown. Those positions are scaled so that the trains' positions on the chart are exactly the same as the trains' positions on Figure 31 where defining the minimum distances in track design on the single track arrangement. The distances are also shown on the Y axis. On the X axis, there is travel time reflected as defined in equations (21) to (24). The charts represent train travel, for example the line ‘Train travel M->R’ represents a train travel from ‘Train position 2’ to ‘Train position 3’. The distance to travel is defined in equation (14) as $s_{M->R}$. The average maximum train speed for that trip is $\Delta v_{M->R}$. The train travel will take time $\Delta t_{M->R}$.

The chart presents constant train travel with maximum speed in the shortest possible distance. In a real situation the train is stopping within the travel distance for reasons such as: railway line capacity limitation (there are a number of trains that can enter the railway junction and other trains must wait unless they are synchronised and there is no other interruption), railway interlocking processing, train loading and unloading, technical problems (infrastructure or train problems) and others (unpredictable, including catastrophic failures). Let’s have a look into a practical example.

### 6.2.4. Train travel time – practical example

Australia is a major supplier of high-quality coal to both mature and emerging markets, accounting for 54 per cent of world trade in metallurgical coal and 24 per cent of world trade in thermal coal. Coal mining in Australia is an increasingly sophisticated and hi-tech activity. Continuous improvements in mining technology, occupational health and safety and environmental performance have ensured that Australia is an efficient and reliable producer of high quality thermal and
metallurgical coals for the international market. The coal industry is supported by a strong equipment and services sector. Australia has world-class expertise in design, construction and operation of mines, transport systems and loading facilities. Australia also has expertise in training, technical support and project management. [50]

The coal transportation process involves rail and sea transport as well as loading and unloading stations. Coal mines in Australia are located inland and the transport between coal mines and sea ports (on the Australian coasts) is conducted by means of trains being operated within railway arrangements as described in Section 6.2 of this thesis. In short, the coal transportation process is as follows: the train’s wagons are loaded with coal on a loading station located within a rail spur. Once the wagons are fully loaded with coal, the train travels toward sea port through various track arrangements including the one defined on Figure 4.

The train trip will be analysed from passing loop 1 to the rail spur that reflects a typical scenario in most mining sites in north Queensland. The same rail arrangement, as defined on Figure 4, will be used in this practical example. It will be signalled with mechanical points and semaphores as reflected on Figure 34. The following modifications will be applied to this practical example, so that it will become more of a real life example:

- A coal loading station has been added on the rail spur
- A level crossing has been installed between passing loop 1 and the railway junction.

The modified arrangement has been reflected on Figure 60.

![Figure 60 Modified rail arrangement signalled with mechanical points and semaphores](image-url)
There are also four train symbols (two red trains and two blue trains) on that drawing:

- Two red trains – ‘Train 1 start’ on the up direction of passing loop 1 and ‘Train 1 stop’ on the down direction of the rail spur, represent a train travel between passing loop 1 and rail spur

- Two blue trains – ‘Train 2 start’ on the return direction from the rail spur and ‘Train 2 stop’ on the down direction of the passing loop 1, demonstrates a train travel between rail spur and passing loop 1.

Let’s imagine an empty (unloaded) train usually stops at passing loop 1 (‘Train 1 start’) to wait until a loaded train (Train 2) will clear the passing loop 1 travelling from the rail spur. ‘Train 2 stop’ shown on the drawing clears ‘Train 1 start’. The unloaded train then starts travelling towards the railway junction. Considering the signalling system gives the authority to proceed through the railway junction, the train travels without stopping. However, the train authority not being given for the train driver at the railway junction will stop the train. Should this be the case the train waits until the railway interlocking processes its functions to give the authority for the train to proceed to the rail spur. Within the rail spur, there will be a loading station and the train will stop and accelerate when necessary to load each wagon with coal before leaving the rail spur. There could also be waiting time for signalling authority to leave the rail spur before the freshly loaded train approaches the railway junction again.

The level crossing installed between passing loop 1 and the railway junction protects train operations from traffic and pedestrians crossing the track.

Applying the methodology on analysing minimum distances, defined in Section 6.2.1, it is necessary to take into consideration the new infrastructure changes when calculating \([s_{s1}]\) and \([s_{sr}]\). These changes are presented on Figure 61 and Figure 62.

On Figure 61, there are two additional distances added to clear the level crossing from the train \([s_{LX,c1}]\) and \([s_{LX,c2}]\). Those distances are defined as level crossing clearance and are measured from the centre line of the level crossing. The striking points of the level crossing activation should also be taken into consideration. Thus, if the end of train is still within the striking points of the level crossing the crossing...
may still be activated. Therefore the level crossing clearance distances shall be long enough.

Modifying equations (8) and (9) to account for the additional distances related to the level crossing, the new distance between passing loop 1 and the railway junction will need to be considered as follows:

\[ s_{c1} = s_{bd4} + s_{c_{\text{max}}} + s_{L_{X}} + s_{L_{X}} + s_{c_{\text{max}}} + s_{bd4} \]  

(25)

On Figure 62, the coal loading station influenced the addition of two distances \([s_{t_{\text{max}}}]\) and \([s_{\text{load}}]\). If the train is approaching the loading station ('Train 1 stop') and if it has to stop in front of the loading station, then it would be necessary to fully accommodate the train within the rail spur. That requires the distance \([s_{t_{\text{max}}}]\). Within the rail spur there is also the length of loading station that has to be taken into consideration \([s_{\text{load}}]\).

The equation (5) for rail spur minimum length \([s_{rs_{\text{min}}}]\) has been modified to suit to account for the additional distances.

\[ s_{rs} = s_{bd7} + s_{c_{\text{min}} 4} + s_{t_{\text{max}}} + s_{\text{load}} + s_{t_{\text{max}}} + s_{bd15} + s_{bd16} \]  

(26)

It is also important to mention it is very unlikely that the train continues without stopping in real train travel (like shown on Figure 59), especially where a signalling system is involved.

The travel M->R and R->M in the practical example will look like the one presented on Figure 63.

Train 1 starts from passing loop 1, where after interlocking processing time \([T_{IP1}]\) it travels towards the railway junction. It has been stopped at the railway junction stop signal 2 for time \([T_{IP2}]\). Once the proceed authority has been given Train 1 travels to the entrance of the rail spur and it is stopped there for time \([T_{IP3}]\) before travelling further to the coal loading station. Train 1 travels on the rail spur with significantly
lower speed and stops at the coal loading station to start the coal loading process and again lowering its speed. Then the Train 2 (loaded with coal) starts its travel. Initially, it is stopped at semaphore SRS4, where it gets authority after time \( [T_{IP4}] \) to travel to the railway junction. Train 2 is stopped at the railway junction for time \( [T_{IP5}] \) to receive authority to proceed to passing loop 1. Train 2 travels toward passing loop 1 is stopped at the entrance to the passing loop 1 for the time \( [T_{IP6}] \) to finally go to the passing loop 1 and stop in position ‘train 2 stop’.

![Figure 63 Train travel between passing loop 1 and railway spur in practical example](image)

Accounting for the changes, equations (21) and (22) look as follows:

- Unloaded train travel from the passing loop 1 travels M→R on the railway junction to the rail spur

\[
\Delta t_{M\rightarrow R} = T_{IP1} + \frac{(s_{bd3} + s_{c\_min} + s_{bd20})}{v_{pl1}} + \frac{\Delta s_{s1}}{v_{s1}} + T_{IP2} + \frac{\Delta s_{ij}}{v_{ij}} + \frac{\Delta s_{s3}}{v_{s3}} + T_{IP3} + \frac{(s_{bd7} + s_{c\_min} + s_{t\_max})}{v_{rs1}} + \frac{\Delta s_{s1}}{v_{s1}} + T_{IP4} + \frac{\Delta s_{s3}}{v_{s3}} + T_{IP5} + \frac{(s_{bd20} + s_{c\_min} + s_{t\_max} + s_{bd21})}{v_{pl1}} \tag{27}
\]

- Loaded train travel from the rail spur goes R→M to complete its mission at the passing loop 1

\[
\Delta t_{R\rightarrow M} = T_{IP4} + \frac{s_{bd16}}{v_{rs2}} + \frac{(s_{c\_min} + s_{bd7})}{v_{rs3}} + \frac{\Delta s_{s3}}{v_{s3}} + T_{IP5} + \frac{\Delta s_{ij}}{v_{ij}} + \frac{\Delta s_{s1}}{v_{s1}} + T_{IP6} + \frac{(s_{bd20} + s_{c\_min} + s_{t\_max} + s_{bd21})}{v_{pl1}} \tag{28}
\]
Looking into the chart on Figure 63, train travel times defined on the chart can be described using the following formulas:

\[
T_1 = \frac{(s_{bd3} + s_{c_{-} min 2} + s_{bd20})}{v_{pl1}} + \frac{\Delta s_{r1}}{v_{r1}}
\]  
(29)

\[
T_2 = \frac{\Delta s_{j}}{v_{j}} + \frac{\Delta s_{x3}}{v_{x3}}
\]  
(30)

\[
T_3 = \frac{(s_{bd7} + s_{c_{-} min 4} + s_{1_{-} max})}{v_{r1}}
\]  
(31)

\[
T_4 = \frac{(s_{load} + s_{1_{-} max} + s_{bd15})}{v_{rs2}}
\]  
(32)

\[
T_5 = \frac{s_{bd16}}{v_{rs2}} + \frac{(s_{c_{-} min 4} + s_{bd7})}{v_{x3}} + \frac{\Delta s_{x3}}{v_{x3}}
\]  
(33)

\[
T_6 = \frac{\Delta s_{j}}{v_{j}} + \frac{\Delta s_{x1}}{v_{x1}}
\]  
(34)

\[
T_7 = \frac{(s_{bd20} + s_{c_{-} min 2} + s_{1_{-} max} + s_{bd21})}{v_{pl1}}
\]  
(35)

Having defined travel times and interlocking processing times, the equations (27) and (28) can be finally presented as follows.

\[
\Delta t_{M->R} = T_{jp1} + T_1 + T_{jp2} + T_2 + T_{jp3} + T_3 + T_4
\]  
(36)

\[
\Delta t_{R->M} = T_{jp4} + T_5 + T_{jp5} + T_6 + T_{jp6} + T_7
\]  
(37)

Analysing train operations M->R and R->M as presented on Figure 63 assuming a next train M->R (“Train 1 start”) can be authorised only when train R->M is in position “Train 2 stop” in a 24 hour clock and taking into consideration various interlocking processing times, assuming train stops at every railway junction, a number of train cycle trips can be calculated using equations (36) and (37). The results of those calculations have been presented on Figure 64.
The parameters used when calculating travel times are shown on the right hand side of the chart.

At those parameters, the chart selects the type of interlocking to be implemented on railway junctions within passing loop 1, railway junction and rail spur. If the railway interlocking gives authority to the train in 3 minutes, there can be eight full cycle train trips within 24 hours, including loading the trains in the coal loading station. If the interlocking processing time is 30 minutes, there can be only four full cycle train trips per day.

The proposed minimum travel distance model is applicable to each type of railway interlocking defined in this thesis.

The same applies to calculation of the travel time values-equations (29) to (35).

Using the methodology described in this thesis, transport planners can now start developing railway interlocking requirements in the planning phase that form the basis for selection of the interlocking technology.

### 7. Performance evaluation

Chapter 7 describes railway interlocking performance measures to be able to assess interlocking technologies to meet the requirements specified by operational conditions on a railway junction. The formal method has been developed for the purpose of comparing various technology implementations on a single, bidirectional railway junction.

So far railway interlocking processes have been specified and they have been categorised in three main groups of existing railway interlocking: ‘manual - human interlocking’, ‘mechanical interlocking’, and ‘electrically powered interlocking’ (Section 5). Within each of those categories there can be a number of railway interlocking technologies and a number of various signalling system components.
applicable. Therefore, it is crucial to find some performance measures to evaluate railway interlocking technology in the context of its suitability on a railway junction.

Evaluating railway interlocking technology is always difficult and is conducted from many perspectives. First is obviously safety, however taking into consideration that railway interlocking is standardised and fulfilling requirements of rail infrastructure, and meeting the safety criteria defined by those standards and requirements, the question is which one is better? Naturally, a cost parameter comes into play. Usually a financial planner will ask which railway interlocking technology is cheaper. The answer is not that obvious because there are a few more parameters that influence the evaluation: railway interlocking processing time, railway signalling system lifecycle cost and railway interlocking functionality:

- Railway interlocking processing time \( T_{IP} \) is a processing time to signal a train and return the railway interlocking to its initial state after train passage. The processing time has direct impact on railway junction capacity. Longer processing time can sometimes be unacceptable and therefore will influence certain type of technology.

- Railway junction signalling system cost \( C_{SS} \) is a lifecycle cost of implementing and operating a railway signalling system. Implementation cost includes designing the railway signalling system implementation, procuring the required railway signalling system components including system licensing, installation of the system, testing the entire system installation and commissioning the railway signalling system. Operational cost is understood as the cost of maintaining the railway signalling system, renewing the system when necessary and removing and investigating any failures. Nowadays, the railway signalling system lifecycle cost is a very important parameter in our economy driven world.

- Railway interlocking functionality \( F_{RI} \) – defined as a number of functions within railway interlocking to secure train movement and additionally enhance functionality of other systems that can be achieved by cooperating with other systems. Current signalling systems work with minimal functionality restricted only to those functions that keep train operations safe often not looking into opportunities to enhance other systems that are responsible for making railway transport more available and reliable.

In the literature reliability \( R \) is defined as the probability of a device performing its purpose adequately for the period of time intended under the operating conditions encountered [49]. Reliability is a measure of successful system operation over a period of time or during a mission. During the mission time, no failure is allowed. Availability is a measure that allows for a system to be repaired when failures occur. Availability is defined as the probability that the system is in normal operation. Availability \( A \) is a measure of successful operation for repairable systems [51].

It is worth mentioning that railway signalling system availability as well as theoretical and practical railway signalling system reliabilities are important parameters that have to be considered when analysing railway interlocking functionality:
Railway signalling system availability \( A_{SS} \) will be defined as probability that the railway signalling system is in normal operation.

Theoretical railway signalling system reliability \( R_{TSS} \) will be defined as calculated, theoretical probability railway signalling system implemented on a railway junction (as defined in Section 5 Implementation of interlocking on railway junction) performing its purpose adequately for the period of time to which the system application has been designed for.

Practical railway signalling system reliability \( R_{PSS} \) will be defined as measured, practical probability railway signalling system implemented on a railway junction (as defined in Section 3 Railway junction description) performing its purpose adequately for the period of time to which the system application has been designed for.

The desire would be to increase the functionality; however, it may have a direct impact on theoretical and practical signalling system reliability and railway signalling system availability. An example of positive impact is widely described in [52] where authors are referring to an innovative condition monitoring to improve points practical reliability. The positive impact can be negated when the technology used in innovative points condition monitoring requires more maintenance to make the system available than maintaining the actual points.

### 7.1. Railway interlocking processing time \([T_{IP}]\)

Consistent estimation of the railway interlocking processing time will be conducted using the previously defined railway interlocking processes:

- Manual (human) interlocking
- Mechanical interlocking (Mechanical points and Mechanical points and semaphores)
- Electrically powered interlocking (Relay interlocking and Computer based interlocking - CBI).

#### 7.1.1. Manual (human) interlocking processing time \([T_{IP_{MI}}]\)

Coming back to the algorithm of the manual (human) interlocking reflected on Figure 9, there is a processing time associated with each state of that algorithm.

In the very first state Check train proceed authority, the flagman obtained authority to control trains on the railway junction, the flagman is equipped with flags and the operational conditions on the junction are met to be able to further control train movement. Therefore there will be various times related to the activities conducted in the state of checking train proceed authority. A sum of the times can be defined as checking train proceed authority time \([T_a]\).
Coming back to the algorithm, in the next state the flagman then checks the points position looking if the points are positioned normal or reverse. If the points are in the correct position, can the points be passed safely by a train? A sum of the activities related to this state will be defined as checking points position time \( T_\beta \).

Further down the flagman displays a proceed aspect by lowering the red flag and raising the green flag. Once again there will be times related to those tasks and their sum will be known as displaying proceed aspect time \( T_\zeta \).

The train driver received a clear indication to proceed, therefore now the train starts accelerating to travel through the railway junction. The time associated with the train travel through the junction will be defined as proceed train \( T_\eta \).

When the train left the railway junction there are tasks performed by the flagman to prepare the route for the approaching train and therefore another time related to those steps – time to prepare route for approaching train \( T_\theta \).

Finally before the entire interlocking process starts again the flagman performs all checks again, which take a time \( T_\iota \).

Therefore, the total railway interlocking processing time for manual (human) interlocking \( T_{\text{IP}_\text{MI}} \) will be a sum of the times listed above.

\[
T_{\text{IP}_\text{MI}} = T_\alpha + T_\beta + T_\zeta + T_\theta + T_\iota
\]  

(38)

In the case that the flagman needs to change the points position, the total railway interlocking processing time for manual (human) interlocking will increase its value by the time of changing points position \( T_\gamma \) and time of checking points position again \( T_\beta \). The equation (39) shows the changes in the formula for total minimal railway interlocking processing time for manual (human) interlocking.

\[
T_{\text{IP}_\text{MI}} = T_\alpha + 2T_\beta + T_\zeta + T_\theta + T_\iota + T_\gamma
\]  

(39)

On the algorithm presented on Figure 9, there are states associated with points failure and proceed aspect failure and consequently additional checks that have to be performed to return the interlocking process to its initial state. The times are as follows:

- Points movement system fault time \( T_\delta \)
- Perform all checks again time \( T_\iota \)
- Green flag system fault time \( T_\iota \)
- Perform all checks again time \( T_\iota \).

Assuming there is one points movement system fault and one green flag system fault the equation (39) needs to be modified including all four times listed above and two more check train proceed authority times, two more check points position times and one more display proceed aspect time.
The total railway interlocking processing time for manual (human) interlocking will depend on the number of failures as well as changing the points position.

7.1.2. Mechanical interlocking processing time

As defined in Section 5.2, there are two types of mechanical interlocking and the interlocking processing time will be analysed below for both types separately.

7.1.2.1. Mechanical points processing time \([T_{IP, MP}]\)

An algorithm of interlocking that mechanically locks the points has been presented on Figure 11. Similar to the manual (human) interlocking processing time, there are times associated with each of the algorithm steps.

The first two times of interlocking process will be similar to manual (human) interlocking and they are the following: checking train proceed authority time \([T_\alpha]\) and checking points position time \([T_\beta]\).

Further down in the algorithm (Figure 11), the train has to be authorised to proceed. It can be done by a flagman, by a radio communication, by computer management system that communicates with the train. The time associated with this function is defined as authorising train to proceed time \([T_\mu]\).

In the next step, the train is travelling through the railway junction. This is happening in a time further known as proceeding train time \([T_\nu]\).

Once the railway junction is clear there will be a time associated with setting up the way for a next train. This time is recognised as preparing route for approaching train time \([T_\xi]\).

Finally the system needs verification of its current state before the next train can be signalled. The time will be called performing all checks time \([T_\omega]\).

A sum of times for mechanical points interlocking defined above will create the total minimal railway interlocking processing time for mechanical interlocking – mechanical points (Mechanical points processing time \([T_{IP, MP}]\)).

\[
T_{IP, MP} = T_\alpha + T_\beta + T_\mu + T_\nu + T_\xi + T_\omega
\]  

(41)

When a points position change is required the interlocking process will be longer because additional operations will be needed and therefore, additional times associated with those operations shall be considered. They are the following:
• Insert operator’s key time \([T_\gamma]\)

• Turn operator’s key to unlock lever 1 time \([T_\theta]\)

• Move lever 1 to opposite position time \([T_\iota]\)

• Move lever 2 to opposite position time \([T_\kappa]\)

• Turn operator’s key to lock lever 1 and remove the key time \([T_\lambda]\).

Once those operations are completed and the points position is changed the interlocking process returns to preparing the route for the approaching train and through performing all checks it starts from checking train proceed authority.

The interlocking processing time in that case will be described by the equation (42) below.

\[
T_{IP_{-MP}} = 2T_\alpha + 2T_\beta + T_\mu + T_\nu + T_\zeta + T_\sigma + T_\theta + T_\iota + T_\kappa + T_\lambda
\] (42)

The equation (42) becomes more complicated when the interlocking encounters some problems. Additional operations times have to be added:

• Operator’s key system fault time \([T_\delta]\)

• Perform all checks again time \([T_\iota]\)

• Ground frame system fault time \([T_\sigma]\)

• Perform all checks again time \([T_\kappa]\)

• Authority system fault time \([T_\lambda]\)

• Perform all checks again time \([T_\rho]\).

The total railway interlocking processing time for mechanical points processing time will therefore be a combination of interlocking processing times depending additionally on interlocking equipment failures as well as the necessity to change the points position.

7.1.2.2. Mechanical points and semaphore processing time \([T_{IP_{-MPS}}]\)

The situation becomes a little bit more complicated where there is more equipment involved in interlocking processing. The algorithm for mechanical interlocking where points and semaphores are involved was previously presented and described in Section 5.2.2.

The first step of the process will be similar to the previously defined two types of interlocking – checking train proceed authority time \([T_\alpha]\). Assuming there are no
problems with the current train proceed authority there is a step to unlock lever 5 that takes unlock lever 5 time \([T_{β}]\). Following that operation, the interlocking will process checking points position time \([T_{τ}]\).

The next operation is important to understand as in the checking points position state the interlocking process allows selection of the required route. Therefore in the next step, assuming the route from M<->N is being prepared, the process will follow to the state of changing points position (υ) where the time associated with interlocking operations will be called changing points position time \([T_{υ}]\) noting that it can have value ‘0’ in the case that the points are in the normal position.

Still following the M<->N route, the next selection in the interlocking process depends on the direction of train travel. Assuming the train travels from semaphore S1 normal direction lever 1 needs to be pulled giving authority to the train to proceed from semaphore S1. The operation takes time that will be further known as pull level 1 time \([T_{φ}]\). Then the train commences its travel from S1 or continues its travel passing semaphore S1 to travel through the railway junction leaving the points completely. The time associated with this process is defined as proceed train from S1 time \([T_{χ}]\). Further down to complete the interlocking process the interlocking system is preparing a route for approaching train in prepare a route for approaching train time \([T_{μ}]\) and performing all checks again \([T_{ν}]\).

A minimal time of mechanical points and semaphore processing will therefore be described by following equation:

\[
T_{IP\_MPS} = T_{α} + T_{β} + T_{τ} + T_{υ} + T_{φ} + T_{χ} + T_{μ} + T_{ν}
\]  

(43)

In the mechanical points and semaphores interlocking process there will be more minimal times. The other minimal time will be associated with route M<->N and train approaching the railway junction from semaphore S3. The minimum time in this case will be as follows.

\[
T_{IP\_MPS} = T_{α} + T_{β} + T_{τ} + T_{υ} + T_{φ} + T_{ρ} + T_{μ} + T_{ν}
\]  

(44)

Where:

\(T_{α}\) is defined as pull lever 3 time

\(T_{υ}\) is proceed train from S3 time.

Analysing the minimal time of mechanical points and semaphore processing for route M<->R and assuming the train operation is conducted from semaphore S2, the minimum time will be:

\[
T_{IP\_MPS} = T_{α} + T_{β} + T_{τ} + T_{χ} + T_{κ} + T_{μ} + T_{ν}
\]  

(45)

Where:

\(T_{τ}\) – change points position time [the value will be ‘0’ if the points are in reverse position]
In the case that the route is set from semaphore S4, the equation (45) will be modified as follows:

\[ T_{IP_{-MPS}} = T_{\tau} + T_{\mu} + T_{\zeta} + T_{\xi} + T_{\alpha} + T_{\mu} + T_{\nu} \]  

(46)

Where:

- \( T_{\xi} \) – pull lever time
- \( T_{\mu} \) – proceed train from S2 time.

Going from a minimal mechanical points and semaphore processing time to a maximum processing time, there are times associated with equipment failures. They are as follows:

- Time associated with semaphore fault
  - \( T_{\psi} \) – Semaphores system fault time, the time of semaphores system fault until restored
  - \( T_{\alpha} \) – Perform all checks again time

- Time associated with lever 5 fault
  - \( T_{\iota} \) – Lever 5 system fault time, the time until lever 5 operation is restored
  - \( T_{\eta} \) – Perform all checks again time

- Time associated with points fault
  - \( T_{\varsigma} \) – Points movement system fault (reverse), the time until points operation is restored
  - \( T_{\sigma} \) – Perform all checks again time
  - \( T_{\iota} \) – Points movement system fault (reverse), the time until points operation is restored
  - \( T_{\eta} \) – Perform all checks again time

- Time associated with semaphore 1 system fault
  - \( T_{\omega} \) – Semaphore 1 system fault time, the time until semaphore 1 operation is restored
  - \( T_{\omega} \) – Perform all checks again time

- Time associated with semaphore 2 system fault
\( T_\theta \) – Semaphore 2 system fault time, the time until semaphore 2 operation is restored

\( T_1 \) – Perform all checks again time

- Time associated with semaphore 3 system fault

\( T_\omega \) – Semaphore 3 system fault time, the time until semaphore 3 operation is restored

\( T_E \) – Perform all checks again time

- Time associated with semaphore 4 system fault

\( T_\pi \) – Semaphore 4 system fault time, the time until semaphore 4 operation is restored

\( T_\rho \) – Perform all checks again time.

Depending on how the mechanical points and semaphores interlocking behave the times listed above may or may not be part of maximum processing time.

### 7.1.3. Electrically powered interlocking processing time \([T_{\text{IP,EPI}}]\)

Relay interlocking and Computer based interlocking (CBI) use the same electrically powered interlocking algorithm. Each function of those types of interlocking is implemented using different technologies and different techniques; however, all functions for both types of interlocking are the same. Therefore, the processing time definition associated with each interlocking operation will be the same for both interlocking types.

The interlocking process for electrically powered interlocking has been described and detailed in Section 5.3.

First step of the algorithm is similar to the previously described interlocking and requires check train process authority time \([T_\alpha]\) to be processed. In that step the interlocking actually understands if the request is a route request (a request to signal a train) or points request (a request to move the points allowing its maintenance).

### 7.1.3.1. Route request

The interlocking is now looking into checking route selection that happens in check route selection time \([T_\gamma]\). There are four potential routes that can be selected: S1->N, S3->M, S1->R and S4->M.
Following the description in Section 5.3, only processing times related to route S1->N will be analysed below.

Once the route is selected and checked it is available the interlocking pre-selects the route in the pre-select route S1->N time \([T_δ]\) allowing for route cancellation, checking if other routes are pre-selected and confirming S1 signal displays a red aspect and the route S1->N has been preselected.

Then, the interlocking processes the next operations at the time of checking track availability \([T_ν]\). It looks into tracks 2T, 3T, 4T and 5T if they are free, checking if the route has not been cancelled.

Further down the algorithm checks the points position is a check points position time \([T_ξ]\). In the case that points requires their position changed there will be a control points normal (R->N) time \([T_ρ]\) associated with the operation, otherwise the interlocking processes further requests to check if other routes are locked and if there is a cancellation of the route that take a check if there is opposite route set time \([T_ς]\).

The interlocking now is locking the route and approach locking the route S1->N – Lock S1->N Approach lock S1->N time \([T_σ]\) to be able to display a proceed signal on S1. This operation takes the display proceed aspect on S1 time \([T_τ]\).

The train is not coming through the railway junction. The interlocking seeks to detect train operated route release. The time associated with detecting that train occupied track 2T is defined as detect train operated route release time \([T_ό]\).

As soon as the train is detected on 2T, interlocking processes display a red aspect on S1 also checking if S1 displays a red aspect and also waiting on the train to pass the junction releasing all relevant train detection units. Those operations will be conducted in display red aspect on S1 time \([T_υ]\).

The last processing time is associated with unlocking the route S1->N and is defined as unlock the route S1->N time \([T_ω]\).

A sum of processing times relevant in electrically powered interlocking defined so far makes a minimal processing time of electrically powered interlocking \([T_{IP\_EPI}]\).

\[
T_{IP\_EPI} = T_α + T_γ + T_δ + T_ν + T_ξ + T_σ + T_τ + T_ω + T_δ + T_ω
\] (47)

There are other processing times within the route S1->N processing that can be involved in the case of equipment failures, signalman operation or/and situation on track. Those times are listed and described below:

- Time associated with route cancellation in S1->N pre-selection process

  \(T_θ\) – Display red aspect on signal S1 time

  \(T_ι\) – S1 red aspect fault time, the time until the S1 red aspect is restored to correct operation
\( T_{\kappa} \) – Deselect route S1->N time

- Time associated with technical problems displaying S1 red aspect

\( T_{\lambda} \) – S1 red aspect fault time, the time until the S1 red aspect is restored to correct operation

\( T_{\mu} \) – Perform all checks again time

- Time associated with technical problems when moving the points from reverse to normal

\( T_{\sigma} \) – Points movement R->N system fault time, the time until points are working correctly again

\( T_{\tau} \) – Perform all checks again time

- Time associated with technical problems when displaying a proceed aspect

\( T_{\delta} \) – Unrecognised state of proceed aspect S time, the time until interlocking comes back to the initial state

\( T_{\iota} \) – S1->N Proceed aspect fault time

\( T_{\iota} \) – Perform all checks again time

- Time associated with displaying a Red aspect on signal S1 in the case of signal S1 not displaying a proceed aspect or route request is cancelled post displaying a proceed aspect

\( T_{\upsilon} \) – Display Red aspect on signal S1 time

\( T_{\psi} \) – S1 red aspect fault time, the time until the S1 red aspect is restored to correct operation

\( T_{\chi} \) – Perform all checks again time

\( T_{\psi} \) – Release approach locking time

\( T_{\omega} \) – Unlock S1->N time

- Time associated with technical problems displaying S1 red aspect when train entered the section

\( T_{\varepsilon} \) – S1 red aspect fault time, the time until the S1 red aspect is restored to correct operation

\( T_{\eta} \) – Perform all checks again time.
7.1.3.2. Points request

Coming back to the beginning of the interlocking process, let us assume the next step is to support maintenance activities on the points and there is a request to change the points position from Reverse to Normal. Obviously the first processing time in the process of requesting the point movement will be $T_\alpha$ mentioned above that is common for route request and points request and where the interlocking algorithm checks if this request is not route request then what kind of points request it is. In the case that this is a points request $R \rightarrow N$ the interlocking initialises points request $R \rightarrow N$ in the processing time $[T_r]$. The next time in the interlocking process is allocated for controlling the points $R \rightarrow N$ $[T_J]$ where the physical movement takes place. Once the points are locked and detected the operation is finished and the algorithm progresses to the state of checking trains proceed authority.

Having said that a minimal time for points request from Reverse to Normal will be described as follows:

$$T_{IP\_EP} = T_\alpha + T_J$$

(48)

In the points request part of the electrically powered interlocking, there are other states to which the algorithm can enter. Times associated with those states are defined below:

- Time associated with cancellation of points request $R \rightarrow N$
  
  $T_C$ – Cancel points request time, where the operator cancelling the points request will stop processing the request in a cancel points request time returning the algorithm to initial state

- Time associated with cancellation of points request in the case the points are not detected in Reverse position
  
  $T_S$ – Cancel points request $R \rightarrow N$ time

- Time associated with points system fault time, the time until points are working correctly again
  
  $T_I$ – Points system fault time

- Time associated with points movement system fault
  
  $T_{IB}$ – Points movement $R \rightarrow N$ system fault time, the time until points are working correctly again

Calculating the total electrically powered interlocking processing time for points request that includes times defined above the equation (48) can be utilised where $\Sigma T$ will be a sum of minimal interlocking processing time for the points request $R \rightarrow N$ and other times defined above that are related to points request $R \rightarrow N$. 

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Even different technology and different engineering solution are used when implementing electrically powered interlocking, the times definition in this section will be applicable to both technology and solution of electrically powered interlocking and value of those times will vary depending on technology and solution used. Those times have to be calculated or/and measured separately for each step of interlocking process for each of the technologies and solutions.

7.2. Railway junction signalling system cost

In a process of selecting the proper signalling system for the railway junction (the process will be further known as the signalling investment process), it is extremely important to recognise the cost associated not only with the system implementation on the railway junction but also the cost later on when the system is being maintained and renewed to keep the railway junction design parameters at the same operational level assuring train travel through the railway junction is not delayed by degraded signalling system.

The cost breakdown will be further analysed consistently under manual (human) interlocking, mechanical interlocking (mechanical points and mechanical points and semaphores) as well as electrically powered interlocking. The cost breakdown will often refer to the signalling system layouts for those interlocking that are presented respectively on Figure 7, Figure 10, Figure 12 and Figure 18.

7.2.1. Signalling system cost - Manual (human) interlocking

The elements that take part in the signalling system with manual (human) interlocking are very schematically shown on Figure 7. To analyse the cost it requires a little bit more description.

Figure 7 needs to be further detailed in a signalling plan and layout. Safeworking procedures to safely operate the system have to be written along with the relevant manuals. Then mechanical points are designed for the part relevant for the signalling arrangement only and connection between points to the lever. That is followed by mechanical lever and lever base design and a design for signalling flags.

Once the designs are completed the signalling system component parts and other parts needed to complete the signalling system are purchased allowing further implementation progress. The things that have to be considered are mechanical points design parts, lever mechanical parts, flags [Red and Green], base for the lever and spare parts in the case something fails within the first twelve months of train operations (twelve months is the usual warranty period from most of the suppliers these days).
Signalling system components parts and other parts are delivered to site where they are progressively installed. The installation activities are: install base for the lever, install mechanical lever, install mechanical points parts, connect mechanical points with the lever. At the end of the installation process, the entire installation needs testing to make sure it functions as designed. When the tests are finished the signalling system is commissioned and this activity practically finishes an up-front investment that is usually seen as a big cost. However, there are more activities to come that shall be included in the cost estimate for the signalling system on the railway junction. This cost is related to train operations.

Each time the train is approaching the railway junction, there is a requirement for a flagman to be present on the railway junction to operate the safeworking (flags and points as per the interlocking process described in Section 5.1). To keep the signalling system in an optimal condition, the design manuals usually provide some recommendation on how the signalling system should be maintained. Therefore, a maintainer is needed to maintain the entire installation.

Post warranty (twelve months mentioned above), there may be more parts of the system required to be renewed, repaired or refurbished. Therefore, some allowances have to be made for the following parts: mechanical points parts, lever mechanical parts, flags [Red and Green] and a base for the lever. Finally within the same budget there should be some provision made for lubricant and cleaner purchase. It could be one kind of lubricant or more depending on what the design manual recommends.

7.2.2. Signalling system cost - Mechanical interlocking

The cost structure in the case of a signalling system where mechanical interlocking is involved will be similar. The detailed cost components are described below separately for mechanical points and mechanical points and semaphores.

7.2.2.1. Signalling system cost - Mechanical points [C_{SS_MP}]

The signalling arrangement for the signalling system implemented on the railway junction (where mechanical points interlocking is involved) is schematically shown on Figure 10.

Designing the system implementation, there is a cost associated with the signalling plan and layout, safeworking procedures, manuals, mechanical points design (just signalling arrangement), mechanical points indicator design, mechanical 2 lever ground frame design, mechanical 2 lever ground frame base design, operator’s lock design, keys for operator’s lock design, a design of connection and roddings from points to the ground frame and finally flags design.
The next step is to procure the parts to build the designed system: mechanical points parts, mechanical points indicator complete, operator’s lock complete, keys for operator’s lock, 2 lever ground frame complete, base for the 2 lever ground frame, flags [Red and Green] and supply spare parts in case something fails within twelve months of train operations.

The signalling system component parts are delivered to site and they require installation, therefore, cost associated with the installation should account for the following: install base for the 2 lever ground frame, install mechanical points design parts, install mechanical points indicator complete, install 2 lever ground frame complete, install operator’s lock complete and connect mechanical points with points indicator and 2 lever ground frame.

Once the installation is completed the signalling system shall be tested and there is a cost involved in testing the entire installation as well as further cost when commissioning the system. Please note if there are problems when testing or commissioning the system and installation activities needs to be undertaken the allowances are made in the testing and commissioning cost.

When the system is commissioned and trains start operating there is an operational cost to consider and resources relevant in the safeworking operation are: a flagman to operate safeworking and a maintainer to maintain the entire installation.

Finally, the maintainer needs the following parts of the designed signalling system to keep the safeworking operating at the designed quality level: mechanical points design parts, 2 lever ground frame mechanical parts, mechanical points indicator parts, operator’s lock parts, keys for operator’s lock, flags [Red and Green] and a base for the lever. The maintenance process also requires some lubricant and cleaner that have to be budgeted as well.

### 7.2.2.2. Signalling system cost - Mechanical points and semaphores

#### [CSS_MPS]

Figure 10 shows schematically what is involved in implementing a signalling system with mechanical points and semaphores interlocking. The design cost needs to account for: production of signalling plan and layout, safeworking procedures, manuals, mechanical points and semaphores design (just signalling arrangement), mechanical semaphore design [single arm], mechanical semaphore design [double arm], mechanical semaphore base design [both arms], mechanical 5 lever ground frame design, mechanical 5 lever ground frame base design, connection and roddings from semaphores to the ground frame design and connection and roddings from points to the ground frame design.

Following the design activities, there are procurement activities related to the supply of the signalling system component parts. The parts are as follows: mechanical semaphore [single arm] complete, mechanical semaphore [double arm] complete, mechanical semaphore base [single arm], mechanical semaphore base [double...
arm], mechanical 5 lever ground frame complete, mechanical 5 lever ground frame base, connection and roddings from semaphores to the ground frame [single arm], connection and roddings from semaphores to the ground frame [double arm], connection and roddings from points to the ground frame and miscellaneous [parts needed at installation] plus parts supplied in case the signalling system fails within the first twelve months.

Estimating the signalling system installation cost the following activities shall be considered: install semaphore base [single arm], install semaphore base [double arm], install semaphore [single arm], install semaphore [double arm], install 5 lever ground frame base, install 5 lever ground frame, install and connect roddings from semaphores to the ground frame [single arm], install and connect roddings from semaphores to the ground frame [double arm] and install and connect roddings from points to the ground frame.

When testing the entire installation activities are considered, the cost has to account for: test the entire installation as well as reinstall and retest parts of installation that were incorrect in the first place. Then the cost shall include commissioning the signalling system. This is practically the end of the cost estimate for implementation of the signalling system where mechanical points and semaphores interlocking is considered.

Now the trains are operating and operational cost shall be looked at. Resources first, so a signalman to operate safeworking is needed followed by a maintainer to maintain the entire installation.

The signalling system, through time, will need a procurement of the following parts: mechanical points parts, semaphore parts [single arm], semaphore parts [double arm], 5 lever ground frame mechanical parts, connection and roddings from semaphores to the ground frame parts [single arm], connection and roddings from semaphores to the ground frame parts [double arm], connection and roddings from points to the ground frame parts, mechanical semaphore base [single arm], mechanical semaphore base [double arm] and mechanical 5 lever ground frame base. This is a significantly higher number of spares, therefore it is necessary to include storage cost when the items are not yet installed on site. The maintainer needs some lubricant and cleaner as per the manual recommendations that have to be also accounted for when considering procurement activities.

7.2.3. Signalling system cost - Electrically powered interlocking [CSS_EPI]

The signalling system layout for an electrically powered interlocking is reflected on Figure 18.

The design cost estimate in this case shall include the following: signalling plan and layout, scope of work document that details what type of signalling system is being implemented, what standards shall be used and how the entire system is going to operate, control tables that is a high level document for the production of signalling interlocking design, control centre bit list design that allows designing future
communication between signalling system and the control system, signalling preliminary design [location plan, cable plans, power calculations] that is a high level document to keep the signalling circuit design consistent, signalling circuit design, mentioned earlier signalling interlocking design, control system design, safeworking procedures, manuals, mechanical design [three aspect signal], mechanical design [two aspect signal], mechanical design [three aspect signal with a junction route indicator], mechanical design [base for location case], mechanical design [base for CER/PER/SER], mechanical design [control centre layout], mechanical design [CER building], mechanical design [PER building], mechanical design [SER building], mechanical design [location case], mechanical design [universal signal base to suit all signals], mechanical design [points layout] and mechanical design [rodding set and detection].

Further in the signalling investment process, the procurement cost needs to be considered and activities accounted for are purchasing and supplying: location cases [fully equipped as per signalling circuit design], CER building [fully equipped as per signalling circuit design], SER building [fully equipped as per signalling circuit design], PER building [fully equipped as per signalling circuit design], control centre building [wired complete as per control centre design], train detection units complete, insulated rail joints, signal [two aspect complete], signal [three aspect complete], signal [three aspect complete with a junction route indicator], points machine, rodding set, points detector, location case base complete, signal base [two aspect], signal base [three aspect], signal base [three aspect with a junction route indicator], CER/SER/PER buildings base [materials only], control centre building base [materials only], cable route [material only], cabling as per signalling and control centre design and miscellaneous [parts needed at installation] to complete the entire system. There must be some provision made for purchasing and supplying spare parts in case the signalling system fails.

Once the signalling system parts are available on site, the installation process can commence. The activities that the cost have to be estimated include: install insulated rail joints, install signal base [two aspect], install signal base [three aspect], install signal base [three aspect with a junction route indicator], build CER/SER/PER base, build control centre base, install cable route and pull cables between signalling equipment and building bases [location cases/CER/PER/SER], install cable route and pull cables between location cases and CER/PER/SER, install cable route and pull cables between CER/PER/SER and control centre, install signal [two aspect complete], install signal [three aspect complete], install signal [three aspect complete with a junction route indicator], install points machine, install points detector, install rodding set, terminate signalling equipment near or on track [signals], terminate signalling equipment near or on track [train detection units], terminate signalling equipment near or on track [points machine], terminate signalling equipment near or on track [points detector], install location case complete on the base, install CER complete on the base, install PER complete on the base, install SER complete on the base, install equipment in the control centre building and wire it up, terminate cables in location case, terminate cables in CER, terminate cables in SER, terminate cables in PER and terminate cables in control centre.
An electrically powered interlocking installation requires very thorough testing. The cost of testing includes the following activities: test and certify insulated rail joints, test and certify signal base [two aspect], test and certify signal base [three aspect], test and certify signal base [three aspect with a junction route indicator], test and certify CER/SER/PER buildings base, test and certify control centre building base, test and certify cable route and pull cables between signalling equipment and building bases [location cases/CER/PER/SER], test and certify cable route and pull cables between location cases and CER/PER/SER, test and certify cable route and pull cables between CER/PER/SER and control centre, test and certify signal [two aspect complete], test and certify signal [three aspect complete], test and certify signal [three aspect complete with a junction route indicator], test and certify points machine, test and certify points detector, test and certify rodding set, test and certify termination signalling equipment near or on track [signals], test and certify termination signalling equipment near or on track [train detection units], test and certify termination signalling equipment near or on track [points machine], test and certify termination signalling equipment near or on track [points detector], certify location case complete installed on the base, certify CER complete installed on the base, certify PER complete installed on the base, test and certify equipment installed and wired up in the control centre building, test and certify termination cables in location case, test and certify termination cables in CER, test and certify termination cables in SER, test and certify termination cables in PER, test and certify termination cables in control centre, functionally test signalling circuit design, principles testing of signalling interlocking design, testing control system design and control system design-signalling interlocking design integration testing. The reinstallation activities allowance has to be included in the testing activities.

The next cost is when the signalling system is being commissioned, so the estimate shall include commissioning the system and testing and reinstallation activities during the commissioning.

Once the signalling system is commissioned and trains are operating on the railway junction, there is a resource cost associated with operation of the signalling infrastructure. The cost includes the following resources: a signalman to operate safeworking from the control centre, a maintainer to maintain the electrical installation, a maintainer to maintain the mechanical installation, a maintainer to maintain the telecommunication installation and a signalling maintenance support engineer to support the maintainers.

Also there is a procurement cost relevant in the maintenance process. The following items shall be considered available to the maintenance crew: location case [parts inside the building as per signalling circuit design], CER building [parts inside the building as per signalling circuit design], SER building [parts inside the building as per signalling circuit design], PER building [parts inside the building as per signalling circuit design], control centre building [parts inside the building as per control centre design], train detection unit complete [parts], signal parts [two aspect], signal parts [three aspect], signal parts [three aspect with a junction route indicator], electrical points machine parts, rodding set parts, points detector parts and cabling as per signalling and control centre design [cables for potential replacement]. The maintainers would also need some lubricant and cleaner as defined in the manuals.
7.2.4. Railway junction signalling system cost \([C_{SS}]\)

The next step will be to find the cost of signalling system lifecycle. This will include design, procurement, installation testing and commissioning the signalling system, system operational cost, asset management cost including maintenance, technology life expectancy that drives system replacement and system parts purchase availability. The results of these calculations will depend on some general assumptions, for example:

- length of system operation – it can be assumed that a signalling system will be in operation for 10 years and then will be completely replaced with a new technology or it can be assumed the system will last 75 years and will be properly maintained
- availability of the signalling components and system parts purchase availability – looking at the calculations from a different perspective that parameter can actually influence the length of system operation if the technology lifespan is known.

Going back to the analysis of interlocking on the railway junction, the cost breakdowns of signalling investment on the railway junction described above where manual (human) interlocking, mechanical interlocking and electrically powered interlocking are involved are different; however, looking at those various interlocking the signalling investment costs as detailed in Sections 7.2.1-7.2.3 can be allocated to the following, common categories:

- Design cost – \(C_D\)
- Procurement cost – \(C_{PCS}\)
- Installation cost – \(C_I\)
- Testing cost – \(C_T\)
- Commissioning cost – \(C_C\)
- Resources cost – \(C_R\)
- Procurement cost – \(C_{POB}\).

Therefore, the equation for railway junction signalling system cost is as follows:

\[
C_{SS} = C_D + C_{PCS} + C_I + C_T + C_C + C_R + C_{POB}
\]  

(49)

The signalling investment is funded from two kinds of rail operators’ budgets: capital spending budget [known in the rail industry as CAPEX – Capital Expenditure], from where all major rail investments are funded and operational budget [in the rail industry known as OPEX – Operational Expenditure] that supports rail operations.
Therefore, $C_D$, $C_{PCSB}$, $C_i$, $C_T$, $C_C$ are part of CAPEX, while $C_R$ and $C_{POB}$ are part of OPEX.

7.3. Railway interlocking functionality [FRI]

The next performance measure in the railway junction interlocking evaluation process is railway interlocking functionality. Let's analyse the functionality of manual (human) interlocking, mechanical interlocking (mechanical points and mechanical points and semaphores) and electrically powered interlocking (Relay interlocking and Computer based interlocking - CBI). Those types of interlocking are defined in Sections 7.2.1-7.2.3.

Functions of the interlocking are associated with the conditional steps (rhomb as explained on Figure 8) of interlocking algorithms. When describing the functions symbol F will stand for function and subscript I to XXXXVIII will be used to refer back to the appropriate rhomb of the interlocking algorithm for which the functionality is being analysed.

7.3.1. Manual (human) interlocking

The manual (human) interlocking algorithm is reflected on Figure 9 and functions of the interlocking are as follows:

- Checking flagman raised hand up with the red flag visible to the train driver [F_i]
- Checking the set of points are free, there is no train there and no object that prevents changing the points position [F_{II}]
- Checking the points are positioned as required for the train to travel through the points [F_{III}]
- Checking the points movement has been finalised [F_{IV}]
- Checking for technical problems in the changing points position process [F_V]
- Checking train passage has been completed [F_{VIII}]
- Searching for problems with displaying a proceed aspect using green flag [F_{X}]
- Checking another train is approaching the railway junction to pass through [F_{IX}]
- Searching for problems with displaying a proceed aspect using green flag [F_{X}]

...
• Keeping the interlocking in the Green flag system fault state until the green flag system fault has been removed [FX].

There could be some sub-functions included in the main interlocking function. For example the interlocking process searches for problems with displaying a proceed aspect not defining the problems in greater details. There could be some additional sub-functions within this function that identify problems such as: lack of green flag available near flagman or flagman is not available (e.g. unconscious). However, the sub-functions shall be organised in such a way that the result will be automatically given to the main function related to the searching for problems with displaying a proceed aspect.

7.3.2. Mechanical interlocking

Functions for mechanical points and mechanical points and semaphores interlocking are analysed separately.

7.3.2.1. Mechanical points

The mechanical points interlocking algorithm is presented on Figure 11 and functions of the interlocking are listed below:

• Checking there is no authority for train to proceed [F₁]
• Checking the set of points is free from any train and obstacles [Fᵢ]
• Checking points position [Fᵢᵢ]
• Searching for problems with inserting key into the operator's lock [Fᵢᵢᵢ]
• Keeping the interlocking in Operator's key system fault until the fault is removed [Fᵣ]
• Searching for problems with turning the key inside of operator's key lock [Fᵣᵢ]
• Searching for problems to move lever 1 [Fᵣᵢᵢ]
• Checking that the ground frame operates correctly again [Fᵣᵢᵢᵢ]
• Searching for problems to move lever 2 [Fᵣᵢᵢᵢᵢ]
• Searching for problems with inserting the key into the operator's lock [Fᵣᵣ]
• Checking the lever 1 is unlocked [Fᵣᵣᵢ]
• Checking the lever 2 is unlocked [Fᵣᵣᵢᵢ]
• Checking the operator's key is unlocked post lever 2 movement [Fᵣᵣᵢᵢᵢ]
• Checking the operator’s key has been removed from the operator’s lock [F_{xvi}]
• Searching for problems with making the operator’s key free to remove [F_{xv}]
• Searching for problems with removing the operator’s key [F_{xvi}]
• Checking the authority has been given to the train driver to proceed through the railway junction [F_{xvii}]
• Checking the train has passed the railway junction and the points are not occupied [F_{xviii}]
• Searching for any next train approaching the railway junction [F_{xix}]
• Searching for technical problems when authorising the train to proceed [F_{xx}]
• Keeping the interlocking in the authority system fault until the fault has been removed [F_{xxi}].

Also in this case there could be sub-functions designed in the interlocking process, however only the main functions have been listed that are the absolute minimum that the interlocking has to be equipped with.

### 7.3.2.2. Mechanical points and semaphores

The interlocking algorithm for mechanical points and semaphores has been presented and described in great details in Section 7.1.2.2. The functions of the interlocking are:

• Checking all semaphores arms are positioned horizontally stopping any potential train movements through the railway junction [F_{i}]
• Searching for any technical problem with those semaphores’ arms horizontal positions [F_{ii}]
• Keeping the interlocking in the state of Semaphores system fault until the fault has been removed [F_{iii}]
• Checking lever 5 can be moved [F_{iv}]
• Checking the set of points is not occupied by any train and any obstacle [F_{v}]
• Checking the route M<->N is being prepared [F_{vi}]
• Checking the route M<->R is being prepared [F_{vii}]
• Checking the points are positioned normal [F_{viii}]
• Checking the points are positioned reverse [F_{ix}]
• Searching for any technical problem when changing the points position [F_3]

• Keeping the interlocking in the state Points movement system fault until fault has been removed [F_{xI}]

• Checking for any technical problem with pulling lever 2, therefore any technical problem with semaphore S2 [F_{xII}]

• Checking semaphore 2 system fault has been removed. This function keeps the interlocking in this state [F_{xIII}]

• Checking there is any potential train movement from S2 -> R being authorised [F_{xIV}]

• Checking S2 proceed aspect is displayed [F_{xV}]

• Checking the train has passed the railway junction leaving the points unoccupied [F_{xVI}]

• Checking there are no trains approaching the railway junction points [F_{xVII}]

• Checking the train movement from S4 -> M is being authorised [F_{xVIII}]

• Checking S4 proceed aspect is displayed [F_{xIX}]

• Checking the train has passed the railway junction and the points are not occupied [F_{xX}]

• Checking for any technical problem when pulling lever 4, therefore problems with semaphore 4 [F_{xXI}]

• Keeping interlocking in the Semaphore 4 system fault state until the fault has been removed [F_{xXII}]

• Checking for any technical problem with the points when changing their position [F_{xXIII}]

• Keeping the interlocking the state of Points movement system fault until the fault has been removed [F_{xXIV}]

• Checking the points are in reverse position [F_{xXV}]

• Checking the points are in normal position [F_{xXVI}]

• Checking the train movement from S1 -> N is being authorised [F_{xXVII}]

• Checking the S1 proceed aspect on semaphore S1 has been displayed [F_{xXVIII}]

• Checking train has passed the railway junction and the points are no longer occupied [F_{xXX}]

• Checking train has passed the railway junction and the points are no longer occupied [F_{xXXX}]
• Checking for any technical problems when pulling lever 1, therefore any problems with semaphore 1 [F_{XXX}]

• Checking semaphore 1 system fault has been removed [F_{XXX}]

• Checking the train movement from S3 -> M is being authorised [F_{XXX}]

• Checking semaphore S3 proceed aspect has been displayed [F_{XXX}]

• Checking the train has passed the railway junction and the points are not occupied [F_{XXX}]

• Checking for any technical problem with pulling lever 3, therefore checking for any problems with semaphore 3 [F_{XXX}]

• Keeping the interlocking in Semaphore 3 system fault until the system fault has been removed [F_{XXX}]

• Checking for any technical problem when unlocking lever 5 [F_{XXX}]

• Keeping the interlocking in the state of Lever 5 system fault until system fault has been removed [F_{XXX}].

No sub-functions have been listed above; however, some sub-functions can exist within the main functions.

7.3.3. Electrically powered interlocking
(Relay interlocking and Computer based interlocking - CBI)

The electrically powered interlocking process has been described in great detail in Section 7.3.3 with an algorithm that details the route from signal S1 to Normal. Functions of this interlocking are:

• Identifying set a route request [F_{I}]

• Checking for any Reverse points request (N->R) [F_{II}]

• Identifying if the route S1->N is being selected [F_{III}]

• Checking the route S1->N is available [F_{IV}]

• Identifying if the route S3->M is being selected [F_{V}]

• Checking the route S3->M is available [F_{VI}]

• Identifying if the route S1->R is being selected [F_{VII}]

• Checking the route S1->R is available [F_{VIII}]

• Identifying if the route S4->M is being selected [F_{ix}]

• Checking the route S4->M is available [F_x]

• Checking for any route request cancellation at pre-selection of route S1->N [F_{xi}]

• Checking the route S3->M or S1->R or S4->M are pre-selected [F_{xii}]

• Checking the signal S1 is displaying Red aspect [F_{xiii}]

• Searching for any technical problems at pre-selection route S1->N [F_{xv}]

• Keeping the interlocking in the state S1 Red aspect fault until signal S1 Red aspect fault has been removed [F_{xv}]

• Checking if the route S1->N is pre-selected [F_{xvi}]

• Checking the tracks 2T, 3T, 4T and 5T are working properly and are not occupied [F_{xvii}]

• Searching for any route request cancellation when checking track availability [F_{xviii}]

• Checking if the points P1 are detected in Reverse position [F_{xix}]

• Checking if the points P1 are detected in Normal position [F_{xx}]

• Searching for any technical problem when checking the points position [F_{xxi}]

• Keeping the interlocking in the state Points movement R->N system fault until the points movement system fault has been removed [F_{xxii}]

• Checking the points P1 are locked and detected in Normal position [F_{xxiii}]

• Checking the route S3->M or S1->R or S4->M has been locked [F_{xxiv}]

• Searching for any request to cancel a route at checking the opposite route set [F_{xxv}]

• Checking signal S1 is technically able to display a proceed aspect [F_{xxvi}]

• Searching for any request to cancel a route in the state of Lock S1->N, Approach lock S1->N [F_{xxvii}]

• Checking signal S1 is displaying a proceed aspect [F_{xxviii}]

• Searching for any request to cancel a route in the state of Displaying proceed aspect on signal S1 [F_{xxix}]

• Identifying if the route S4->M is being selected [F_{ix}]

• Checking the route S4->M is available [F_x]

• Checking for any route request cancellation at pre-selection of route S1->N [F_{xi}]

• Checking the route S3->M or S1->R or S4->M are pre-selected [F_{xii}]

• Checking the signal S1 is displaying Red aspect [F_{xiii}]

• Searching for any technical problems at pre-selection route S1->N [F_{xv}]

• Keeping the interlocking in the state S1 Red aspect fault until signal S1 Red aspect fault has been removed [F_{xv}]

• Checking if the route S1->N is pre-selected [F_{xvi}]

• Checking the tracks 2T, 3T, 4T and 5T are working properly and are not occupied [F_{xvii}]

• Searching for any route request cancellation when checking track availability [F_{xviii}]

• Checking if the points P1 are detected in Reverse position [F_{xix}]

• Checking if the points P1 are detected in Normal position [F_{xx}]

• Searching for any technical problem when checking the points position [F_{xxi}]

• Keeping the interlocking in the state Points movement R->N system fault until the points movement system fault has been removed [F_{xxii}]

• Checking the points P1 are locked and detected in Normal position [F_{xxiii}]

• Checking the route S3->M or S1->R or S4->M has been locked [F_{xxiv}]

• Searching for any request to cancel a route at checking the opposite route set [F_{xxv}]

• Checking signal S1 is technically able to display a proceed aspect [F_{xxvi}]

• Searching for any request to cancel a route in the state of Lock S1->N, Approach lock S1->N [F_{xxvii}]

• Checking signal S1 is displaying a proceed aspect [F_{xxviii}]

• Searching for any request to cancel a route in the state of Displaying proceed aspect on signal S1 [F_{xxix}]

• Identifying if the route S4->M is being selected [F_{ix}]

• Checking the route S4->M is available [F_x]

• Checking for any route request cancellation at pre-selection of route S1->N [F_{xi}]

• Checking the route S3->M or S1->R or S4->M are pre-selected [F_{xii}]

• Checking the signal S1 is displaying Red aspect [F_{xiii}]

• Searching for any technical problems at pre-selection route S1->N [F_{xv}]

• Keeping the interlocking in the state S1 Red aspect fault until signal S1 Red aspect fault has been removed [F_{xv}]

• Checking if the route S1->N is pre-selected [F_{xvi}]

• Checking the tracks 2T, 3T, 4T and 5T are working properly and are not occupied [F_{xvii}]

• Searching for any route request cancellation when checking track availability [F_{xviii}]

• Checking if the points P1 are detected in Reverse position [F_{xix}]

• Checking if the points P1 are detected in Normal position [F_{xx}]

• Searching for any technical problem when checking the points position [F_{xxi}]

• Keeping the interlocking in the state Points movement R->N system fault until the points movement system fault has been removed [F_{xxii}]

• Checking the points P1 are locked and detected in Normal position [F_{xxiii}]

• Checking the route S3->M or S1->R or S4->M has been locked [F_{xxiv}]

• Searching for any request to cancel a route at checking the opposite route set [F_{xxv}]

• Checking signal S1 is technically able to display a proceed aspect [F_{xxvi}]

• Searching for any request to cancel a route in the state of Lock S1->N, Approach lock S1->N [F_{xxvii}]

• Checking signal S1 is displaying a proceed aspect [F_{xxviii}]

• Searching for any request to cancel a route in the state of Displaying proceed aspect on signal S1 [F_{xxix}]

• Identifying if the route S4->M is being selected [F_{ix}]

• Checking the route S4->M is available [F_x]

• Checking for any route request cancellation at pre-selection of route S1->N [F_{xi}]

• Checking the route S3->M or S1->R or S4->M are pre-selected [F_{xii}]

• Checking the signal S1 is displaying Red aspect [F_{xiii}]

• Searching for any technical problems at pre-selection route S1->N [F_{xv}]

• Keeping the interlocking in the state S1 Red aspect fault until signal S1 Red aspect fault has been removed [F_{xv}]

• Checking if the route S1->N is pre-selected [F_{xvi}]

• Checking the tracks 2T, 3T, 4T and 5T are working properly and are not occupied [F_{xvii}]

• Searching for any route request cancellation when checking track availability [F_{xviii}]

• Checking if the points P1 are detected in Reverse position [F_{xix}]

• Checking if the points P1 are detected in Normal position [F_{xx}]

• Searching for any technical problem when checking the points position [F_{xxi}]

• Keeping the interlocking in the state Points movement R->N system fault until the points movement system fault has been removed [F_{xxii}]

• Checking the points P1 are locked and detected in Normal position [F_{xxiii}]

• Checking the route S3->M or S1->R or S4->M has been locked [F_{xxiv}]

• Searching for any request to cancel a route at checking the opposite route set [F_{xxv}]

• Checking signal S1 is technically able to display a proceed aspect [F_{xxvi}]

• Searching for any request to cancel a route in the state of Lock S1->N, Approach lock S1->N [F_{xxvii}]

• Checking signal S1 is displaying a proceed aspect [F_{xxviii}]

• Searching for any request to cancel a route in the state of Displaying proceed aspect on signal S1 [F_{xxix}]
• Searching for any technical problem when Displaying a proceed aspect on signal S1 [F.xxx]

• Keeping the interlocking in the state of S1 Red aspect fault until signal S1 Red aspect fault has been removed [F.xxx]

• Searching for approach locking released [F.xxxi]

• Checking if the train occupied train detection unit 2T [F.xxxii]

• Checking signal S1 is displaying a Red aspect [F.xxxv]

• Checking the train has passed the entire section in the route S1->N [F.xxxv]

• Searching for any technical problem when displaying a red aspect on signal S1 [F.xxxvi]

• Keeping the interlocking in the state S1 Red aspect fault until signal S1 Red aspect fault has been removed [F.xxxvii]

• Searching for any technical problems associated with displaying a red aspect on signal S1 [F.xxxvii]

• Keeping the interlocking in the state S1 Red aspect fault until signal S1 Red aspect fault has been removed [F.xxxviii].

Additional functions that are part of the electrically powered interlocking and are related to the points request R->N have been listed below:

• Checking the Normal points movement (R->N) has been requested [F.xxxviii]

• Searching for any points request cancellation and checking train detection unit 3T is occupied [F.xxxv]

• Checking any route is pre-selected or locked [F.xxx]

• Checking the points P1 are detected Reverse [F.xxx]

• Searching for any technical problem when cancelling points request R ->N [F.xxxii]

• Keeping the interlocking in the state of Points system fault until points P1 movement system fault has been removed [F.xxxviii]

• Checking the points P1 are locked and detected in Normal position [F.xxxv]

• Searching for any technical problem when controlling points Normal (R->N) [F.xxxv]

• Keeping the interlocking in the Points movement R->N system fault state until the points movement system fault has been removed [F.xxxv].
It has to be noted that railway interlocking functions can be implemented in various ways depending on the technology used and implementation design prepared by signalling engineers. Especially in the relay and computer based interlocking there is a number of ways to implement the functions using various sub-functions, however, the railway interlocking functionality described above is a great performance measure to limit and optimise the sub-functions to keep the train operations safe and not over build the interlocking.

7.3.4. Railway interlocking functionality \([F_{RI}]\)

In Sections 7.3.1 to 7.3.3, the railway interlocking functions have been described in detail. All functions have been numbered \(F_1\) to \(F_{XXXXVIII}\) and more functions can be added if the railway interlocking requires. Therefore, the equation for railway interlocking functionality looks as follows:

\[
F_{RI} = F_1 + \ldots + F_N
\]

where \(F_1\) to \(F_N\) are representing all functions of railway interlocking being analysed.

7.3.5. Railway signalling system availability \([A_{SS}]\)

System availability is very well defined in literature. The availability theory that suits railway signalling system has been presented and described in [51]:

"Availability is a measure that allows for a system to be repaired when failures occur. Availability is defined as the probability that the system is in normal operation. Availability \((A)\) is a measure of successful operation for repairable systems. Mathematically,

\[
A = \frac{\text{System uptime}}{\text{System uptime} + \text{System downtime}}
\]

Or, because the system is “up” between failures,

\[
A = \frac{MTTF}{MTTF + MTTR}
\]

where \(MTTR\) stands for mean time to repair and \(MTTF\) is mean time to failure is the expected (average) time that the system is likely to operate successfully before a failure occurs.

Mathematically,

\[
MTTF = \int_0^\infty R(t) dt
\]
Where $R(t)$ represents reliability that is defined as the probability that a system will be successfully operating during the mission time $t$.

Looking at the equation (52), a sum of MMTF and MTTR is usually defined as mean time between failures (MTBF) and is an expected value of the random variable time between failures. Figure 65 adopted from [51] shows pictorially the relationship between MTBF, MTTR, and MTTF. From the figure it is easy to see that MTBF is the sum of MTTF and MTTR.

![Figure 65 MTTR, MTBF, and MTTF](image)

Railway signalling system availability $[A_{SS}]$ on a railway junction can therefore be mathematically presented as

$$A_{SS} = \frac{MTTF}{MTBF}$$  \hspace{1cm} (54)

where MTTF is understood as the expected (average) time that the railway signalling system is likely to operate successfully before the system is not functioning as designed. MTBF is a random time between failures of the railway signalling system, failures that cause the railway signalling system to not function as designed. Ideally, the railway signalling system is always available, therefore, railway signalling availability $A_{SS}=1$.

### 7.3.6. Theoretical railway signalling system reliability $[R_{TSS}]$

Reliability is defined as the probability of a device performing its purpose adequately for the period of time intended under the operating conditions encountered. [49][51]

The reliability theory is very well presented in [51]:

“Mathematically, reliability, often denoted as $R(t)$, is the probability that a system will be successfully operating during the mission time $t$:

$$R(t) = P(T > t), t \geq 0$$  \hspace{1cm} (55)
where T is a random variable denoting the time to failure. In other words, reliability is the probability that the value of the random variable T is greater than the mission time t."

Modelling theoretical railway signalling system reliability, a reliability block diagram (RBD) method described in great detail in [51] is applicable where the entire railway signalling system is decomposed to the parts level of signalling system components and the parts are presented in the form of a block diagram. The generic reliability block diagrams have been presented on Figure 66.

Then each block reliability shall be found (once again from calculation for railway signalling system components and component’s parts) before calculating the theoretical railway signalling system reliability [RTSS].

![Figure 66 Generic reliability block diagrams](image)

To understand how to calculate the theoretical railway signalling system reliability the Figure 66 diagram reliabilitys are calculated below:

- for serial RBD system

\[ R_{TSS} = R_1 + R_2 + R_3 \] (56)

- for parallel RBD system

\[ R_{TSS} = \frac{R_4 \cdot R_5}{R_4 + R_3} \] (57)

- for hybrid RBD system

\[ R_{TSS} = R_1 + \frac{R_3 \cdot R_5}{R_4 + R_3} + R_3 \] (58)
Referring back to manual - human interlocking, mechanical interlocking (mechanical points and mechanical points and semaphores) and electrically powered interlocking, in the implementation design process when a signalling system architecture is known, the signalling system can be decomposed to RBD and theoretical railway signalling system reliability calculated. Ideally, the system is reliable 100% and theoretical railway signalling reliability $R_{SS}=1$.

### 7.3.7. Practical railway signalling system reliability [$R_{PSS}$]

Railway signalling reliability block diagrams produced in the railway signalling system implementation design process can be further applied in railway signalling system asset management to calculate practical railway signalling system reliability.

Rail infrastructure operators and managers in the maintenance/asset management process collect real information about equipment and system failures, the faults’ nature and the way the issues have been resolved as well as how long it took to rectify the problem and how long train operations have been delayed. This sort of information is vital for calculating practical railway signalling system reliability and compares the reliability with the theoretical calculations.

When calculating the practical railway signalling system reliability exactly the same formulas are used (example shown in equation (56)-(58)).

It is expected that $R_{PSS}<R_{TSS}$, however, ideally the practical railway signalling system reliability is 100%, therefore $R_{PSS}=1$.

### 7.4. Performance evaluation criteria

In sections 7.1-7.3 of the thesis the following performance measures were defined:

- Railway interlocking processing time [$T_P$]
- Railway junction signalling system cost [$C_{SS}$]
- Railway interlocking functionality [$F_{RI}$]
- Railway signalling system availability [$A_{SS}$]
- Theoretical railway signalling system reliability [$R_{TSS}$]
- Practical railway signalling system reliability [$R_{PSS}$].

Having said that it is relevant to understand relationships between the performance measures. The relationships will be discussed based on the interlocking defined so far.
7.4.1. Railway junction signalling system cost \( [C_{SS}] \) versus Railway interlocking processing time \( [T_{IP}] \)

Figure 67 presents an example of indicative results when comparing cost of signalling system implementation on a railway junction \( [C_{SS}] \) and railway interlocking processing time \( [T_{IP}] \) for the manual - human interlocking, mechanical points interlocking, mechanical points and semaphores interlocking, relay interlocking and computer based interlocking.

![Railway junction signalling system cost-benefit chart](image)

It can be observed on the chart above that manual - human interlocking has a long processing time and the signalling system is relatively inexpensive compared with for example computer based interlocking where the processing time is very short and the cost of the signalling system implementation is much higher.

This comparison can be named a railway junction signalling system cost-benefit chart due to the fact it shows benefit in processing time and the cost associated to gain the benefits.

7.4.2. Railway interlocking functionality \( [F_{RI}] \) versus Railway interlocking processing time \( [T_{IP}] \)

On Figure 68 a railway junction signalling system functions processing chart is presented. It indicatively presents the relationship between the railway interlocking processing time and the number of railway interlocking functions for the previously defined types of interlocking.
7.4.3. Railway junction signalling system cost \([C_{SS}]\) versus Railway interlocking functionality \([F_{RI}]\)

On Fig. 31 a railway junction signalling system functions cost chart has been shown. This chart presents the railway junction signalling system cost and railway interlocking functionality for the types of interlocking described in Section IV, V and VI.
This indicatively shown comparison reflects that there could be interlocking with similar signalling system cost and better functionality that can influence selection of the technology.

Other comparisons can be also made. For example railway junction signalling system cost versus theoretical railway signalling system reliability.

8. Formal method summary

This Chapter summarises how to use those formal method described above in a real application, in particular:

- how to assess a rail transportation process on a railway junction to find the requirements for interlocking processing time $[T_{IP}]$
- how to assess an interlocking to find its interlocking processing time $[T_{IP}]$
- how to further evaluate the interlocking that meets the interlocking processing time requirements using parameters like signalling system cost, functionality, availability and reliability.

8.1. Finding interlocking processing time requirements $[T_{IP}]$

Figure 70 presents an algorithm that provides steps/instruction to find the requirements for interlocking processing time $[T_{IP}]$ using the formal method described in Section 6.
Figure 70 Finding requirements of interlocking processing time $T_{IP}$

The algorithm is pretty much self-explanatory. Initially the planner needs to build a rail arrangement, similar to the one shown on Figure 60. The formal method developed in Section 6 is applicable to a railway junction constructed on a single, bi-directional railway line.
directional rail arrangement. Once confirmed that the method is applicable, the minimum distances shall be calculated as defined in Section 6.1, followed by calculating average maximum velocities (Section 6.2.2) and minimum train travel times (Section 6.2.3).

The next step is to insert minimum train travel times into equations (36) and (37). As a result of the insertion and earlier calculations, there can be a graph constructed allocating intervals of interlocking processing time on the x-ordinate and the number of train cycle on the y-ordinate as required. A graph example has been presented on Figure 64. That graph was produced using the Microsoft Excel package.

The concept of the graph presentation is to graphically show the requirements for the interlocking processing time ($T_{IP}$) at the required train cycle trip. This sets the requirements for an interlocking evaluation.

### 8.2. Assessing an interlocking to find its interlocking processing time [$T_{IP}$]

Figure 71 delivers a step by step algorithm to assess an interlocking processing time to meet the requirements for the interlocking on railway junction set in Section 8.1.

When assessing an interlocking, it is required to check if the interlocking fits into one of the interlocking processes defined in Section 5. Current interlocking on railway junction fits into the interlocking processes defined in Section 5, however, if the interlocking for some reason does not fit into those processes, a modification or even production of a new interlocking process shall be considered. Once a modified/new process is developed the algorithm shall be still applicable for this interlocking.

The next step is to find the processing times associated with each of the interlocking functions. Sometimes it is possible to calculate those times but in most cases they will need to be measured or simply assumed.

Finally, the interlocking processing time can be calculated using the guidance presented in Section 7.1 and the interlocking can be assessed if it meets or doesn’t meet the requirements established in Section 8.1.
8.3. Final evaluation of the interlocking and signalling system on railway junction

There can be a situation that more than one interlocking meets the requirement for interlocking processing time. It is therefore necessary to apply additional performance measures to evaluate the interlocking.
Does the interlocking meet processing time requirements?

No

- No need to assess functionality

Yes

- Assess signalling and interlocking

Does the interlocking meet processing time requirements?

No

- Calculate signalling system cost [Section 7.2]

Is the signalling system cost calculated?

No

- Is the interlocking functionality calculated?

Yes

- Calculate railway interlocking functionality [Section 7.3]

Is the interlocking functionality calculated?

No

- Calculate signalling system availability and reliability [Section 7.3]

Are the availability and reliability calculated?

No

- Produce charts [Section 7.4]

Are the other interlockings assessed?

No

- Compare interlocking processing time, signalling cost, functionality, availability and reliability with other interlockings

Yes

- Post comparison: choose an interlocking most meeting the processing time requirements at lowest signalling cost, at best functionality, availability and reliability

- This is the interlocking and signalling system to be built on the railway junction

Are the other interlockings assessed?

Yes

- Post comparison: choose an interlocking most meeting the processing time requirements at lowest signalling cost, at best functionality, availability and reliability

- This is the interlocking and signalling system to be built on the railway junction

Figure 71 presents steps to further assess the interlocking and related signalling system.

Figure 72 Final assessment of interlocking and signalling system
If the interlocking does not meet the interlocking processing time criteria, there is no need for further assessment; otherwise there is a need to calculate signalling system cost. The process to calculate the signalling system cost is described in Section 7.2.

The next step is to calculate the railway interlocking functionality as guided in Section 7.3 followed strictly by system availability and reliability calculations also described in the same Section of the thesis.

Finally, based on the calculated values, graphs need to be produced as highlighted in Section 7.4. Once this is completed there is a need to compare the results and choose an interlocking that has the best interlocking processing time, lowest signalling cost, highest functionality at the best possible system availability and reliability.

9. Railway junction variations

This Chapter of the thesis discusses the applicability of the method for variances of railway junctions to demonstrate the method is universal and transport planners can consider applying the method to set requirements of railway signalling and interlocking [46] technology and even commence the railway interlocking technology selection process in the transportation planning stage to achieve efficient investment.

There are a few significant differences in railway junction implementations. The track on junctions could have various gauges, the sleepers could be wooden, steel or concrete, the turnout could be left or right hand, it could be built on a railway line curve or on a straight line and could be various sizes (1:9, 1:12, 1:20, etc.). Also looking at the type of trains that passes the turnout, it could be an electric train that needs power supply from overhead or a third rail or the train operated on the line could be only diesel, so that the junction does not need to be electrified. Also, the points could be operated mechanically or/and electrically and could be self-setting (or self-restoring). Finally, the signalling systems operate under many specific principles, there may be a new technology specified or the signalling is a hybrid solution. It is crucial to understand the differences and test if the formalisms are still applicable for those cases.

9.1. Track arrangement with different gauges

Figure 73 schematically depicts a track and points machine arrangement of a railway junction. The turnout is a right hand one, so it means the trains will be diverging or reversing to the right and going straight or normal at the left hand side standing at the front of the turnout looking ahead.
Figure 73 A railway junction – track and points machine arrangement

The picture shows some elements of the points that are instrumental to understanding the differences in the track arrangement. The track gauge is defined as the distance between two rails.

Figure 74 Railway gauges

Various track gauges have been presented on Figure 74. The picture has been constructed on the basis of information presented in [56].

There are various dependencies between track gauges and train speed and between track gauges and train tonnage. From a signalling perspective different
Track gauges could affect track circuit technology, e.g. the resistance of train wheel and axle will vary and will be higher for wider gauges. The track gauge also affects the force with which the turnout blades are moved to change the points position, the dependence is quite obvious the wider track gauge the longer rodding set is required, also more rail component needs to be moved therefore more force is required to move the points.

![Diagram of dual gauge turnout](image)

**Figure 75** An example of a dual gauge turnout

In some cases a railway junction can be built as double gauged. An example is schematically shown on Figure 75. In this case, the turnout is built in such a way that track gauge A is implemented on the entire turnout and track gauge B, which is narrower than track gauge A, has been implemented only in the normal direction.

Additional gauges within a railway junction complicate the implementation from the operations perspective and can double up some track equipment like e.g. track circuits or rodding set, it could also utilise additional equipment to decrease the force necessary to move the points.

### 9.2. Electrified and non-electrified railways

The first railway wagons have been pushed by people, and then pulled by horse and with first steam locomotives pulling more and more wagons. [57]

![Diagram of electrification schematic](image)

**Figure 76** Electrification schematic
All those type of trains do not require any electrification. Diesel locomotives also don’t need any external electrification. For those trains where an electrical engine is powered by energy generated externally, some kind of electrification structure is required to pass the energy into the locomotive.

Figure 76 above provides some idea of what the overhead structure looks like. A train travelling along the railway line closes the electrical circuit between the overhead power line, receiving power through a pantograph mounted on the roof of the locomotive and the rail with traction return system implemented.

Another way of receiving power by a train is a third rail system. Third rail is an insulated construction mounted usually on sleepers with some protective cover as reflected on Figure 77.

The train receives the energy from the third rail through a rail shoe as reflected on Figure 77 and closes the circuit to the rail similar to the case of receiving power supply from an overhead line.

In some implementations, e.g. London Underground, some problems have been found with return currents, intended to be carried by the earthed (grounded) running rail, flowing through the iron tunnel linings instead. This can cause electrolytic damage and even arcing if the tunnel segments are not electrically bonded together. [57] London Underground has introduced a fourth rail, so that train is powered with +420V DC and -210V DC that give a total power of 630V DC.

In terms of voltage supplied to the train, it could be powered with DC or AC power supply. There are four DC electrification systems: 600V, 750V, 1500V and 3kV and three AC train power supply systems: 15kV, 25kV and 50kV.

From the signalling perspective there is a quite significant impact of electrification on some signalling systems, especially those installations with AC power supply can interfere with frequency track circuit technology or axle counter technology. Also, computer based interlocking mounted in a building near the track experience problems if not earthed properly. Therefore it is important that the signalling technology used on the electrified railway junction provides sufficient protection and is fit for purpose.
9.3. Self-setting points

Self-setting points (also referred to as trailable facing or self-restoring points) is a switch and crossing system used at crossing loops to provide an alternative to a full standard switch assembly.[58] An example of self-setting points is shown on Figure 78.

As the train moves towards them (facing), the switch blades are always held open to one side by what is called a snubber system (a hydraulic piston with a delay); this allows the train through on to the loop. A train moving towards the points in the opposite direction (trailable) will force the switch blade open, the snubber will then move the switch back a short time after the train has passed, thus self-setting them back to the standard position. The switch has a manual throw lever for the alternative switch setting. [6]

![Figure 78 Self-setting points](image)

The solution differs from any other points as it is the only implementation where the point position is changed by the train itself and only at the time of the train passing the points. The limitation is that trains facing the points can only travel in one and the same direction, e.g. on the Figure 78 a train facing the turnout will always travel to the right and never goes straight as the points are self-setting only if a train travels from normal to main.

9.4. Hybrid signalling solution

In some cases the signalling technology implemented on a railway junction can be a combination of two or/and more technologies. It is important to acknowledge the fact while seeking some formal method of interlocking process.

- Mechanical signalling with electrical detection

One example in this category can be points operated mechanically with the point position detected manually before a colour light signal display a proceed aspect.

Figure 79 shows electrical point detection of the hybrid signalling solution.
The points are hand operated by means of the points lever [55] equipped with a weight (schematically shown in black). Each of the points movement phase is detected through the detection rodding set by electrical equipment located in a detector box. The detector box is connected to the interlocking as well as to the points (on Figure 79). There are generally three phases of points movement: points locked and detected Normal, points locked and detected Reverse and the situation in between when the points are being moved or they are in a fault/maintenance condition.

- Flagman at a junction with electrically powered interlocking

In the electrically powered interlocking there may be a case where a flagman needs to be introduced, as reflected on Figure 80.

It seems obvious that this situation would happen if the electrically powered interlocking is not functioning properly or a new electrically powered interlocking is being installed or commissioned.

When the electrically powered interlocking is functioning incorrectly the operational rules of infrastructure managers defines how to manage the infrastructure and train operations. The points are manually clipped (a big metal clip mounted underneath the rail where the turnout blades are in normal or reverse position) so that even if something tries to move the points the operation of the points will be prohibited and
locked by the clip. The signals are black, not showing any indications. In this case a flagman is appointed to let trains safely proceed through the junction. Also, it is worth mentioning, if the electrically powered interlocking is not functioning but the power is available the signals display a stop aspect, so in this case different operational rules apply and the flagman is not required.

In the case that the interlocking is being commissioned and there is a need to run “commissioning” trains, the operation on the railway junction is defined by a test and commissioning rules. The signals and interlocking are functioning but are not yet confirmed working properly. Therefore, the signals’ displays are covered by crossed white stripes. During commissioning, the points can be clipped (usually blocked in normal position preventing points operation) or the points can operate electrically. In the commissioning cases mentioned above, the flagman needs to be established to provide a proceed or stop aspect to trains securing “commissioning” trains operation.

9.5. Testing railway junction interlocking

Railway junction interlocking process formalisms require some analysis and testing towards investigating the suitability of the developed formalisms across railway junction differences and Intelligent transport system functions.

9.5.1. Track arrangement with different gauges

None of the interlocking process formalisms presented earlier will be affected by the differences in gauges.

As mentioned in Section 9.1, the biggest challenge for the dual gauge railway junctions is points movement due to increased amount of steel (additional rail) on the turnout. From signalling trackside equipment, the force required to move the points needs to be stronger. However, this is coming down to the selection of the technology and a design of the technology not only in signalling but also in turnout mechanics. For example installing rollers on a turnout decreases the strong force need. Also, installing a ground frame closer to the track will shorten the rodding set. Length of the points lever is also important in the dual gauge scenario.

Having said that looking at the formalisms in Section 5, the ‘manual (human) interlocking algorithm’ in particular, the signalling technology implementation around the states of ‘Checking points position’ and ‘Changing points position’ will be more complicated externally of the algorithm but the core operations in the formalism will be identical for dual gauge or a single gauge implementation of the railway junction.

Similar to the ‘manual (human) interlocking algorithm’, in the ‘interlocking process for mechanical points’, the technology implementation will be different for dual gauge and a single gauge railway junction arrangement only around the state Change points position (state γ) and the formalisms will remain unchanged.
The same rule applies to other formalisms ‘Mechanical points and semaphores’ and ‘Electrically powered interlocking’. In the case of electrically powered interlocking, the technology (a points machine) to change the points position has to be designed in such a way that it can provide a force strong enough to move the blades of both rails (for both gauges) at the same time. In some applications, there is more than one points machine utilised for that purpose.

That situation does not change the formalism on Figure 22 in any way but will create more technology inputs. For example, in the state Are the points detected Reverse? (conditional step XXXXI), there may be more than one input from the points machines that operate the turnout. It is obvious that the interlocking must receive a clear answer that the points are detected reverse, so the technology implementation instruction will include inputs from all relevant points machines operating the dual gauge turnout.

9.5.2. Electrified and non-electrified railways

Section 9.2 defines electrified railways. The biggest challenge for signalling systems in electrified areas is electromagnetic interference. Also relevant is lightning coming from a thunderstorm and wet weather conditions.

The electromagnetic interference is a challenge especially for train detection technology. There are DC track circuits that shall not be used in electrified areas. The rules of allowing technologies are defined by infrastructure managers/owners usually in the equipment type approval process. The type approval certificate provides information about conditions (electrical, weather and operational) in which the approved technology can be used. As part of the process the equipment supplier has to deliver equipment specification and datasheets that specifies technical and operational parameters of the equipment.

In terms of lightning, it may affect the entire signalling system, not just a piece of equipment. Therefore, at the technology implementation phase it is important to design in some kind of lightning protection so that the protection will be damaged rather than the safety critical and expensive equipment.

The electrified and non-electrified railways will have no interference with the interlocking process formalisms even though the technology applied to implement signalling may be different.

9.5.3. Self-setting points

This concept is very clever and effectively cuts out some steps in the interlocking process formalisms. The self-setting points are not installed wherever ground frame technology (they are effectively replacing ground frame technology) or remotely controlled interlocking is implemented. Therefore, looking at the manual (human) interlocking algorithm (Figure 9), the conditional steps related to points position change can be skipped but if the self-setting points concept is equipped in some kind of intelligence to say to the interlocking process that the points are incorrectly
positioned the interlocking process could eliminate potential train derailment if the steps are left in the algorithm.

By analogy the same rule will apply to the interlocking process for mechanical points. However, in this case the interlocking will not have any operator’s key because the ground frame is not there as well as any lever operations. Therefore, the steps could be skipped and even erased that effectively returns the algorithm to the scenario of a manual (human) interlocking algorithm (Figure 9) that has been described above.

In any other situations implementing self-setting points is not practical and will limit line capacity rather than increase it.

### 9.5.4. Hybrid signalling solution

In the hybrid signalling solution on a railway junction like that reflected on Figure 79, one of two formalisms may be applicable: a manual (human) interlocking algorithm (Figure 9) in the case where the proceed and stop aspect is given by a flagman (the junction is usually part of a bigger interlocking) or electrically powered interlocking if the proceed and aspects are implemented by means of a colour light signal.

In the first case the electrical detection technology will input to the algorithm (Figure 9) in the following steps “Are the points in the correct position?” and “Is the points movement finalised?” The electrically powered interlocking will be provided with the input wherever the algorithm mentions points locked and detected.

Analysing the hybrid systems it could be also a flagman signalling an electrically powered interlocking, however, the operational rules will effectively overlay the electrically powered interlocking with a manual (human) interlocking algorithm where the electrically operated points will be manually controlled.

### 9.5.5. Signalling principles

The variety of signalling principles increase the cost of technology due to the fact that suppliers have to maintain so many different parts of equipment and at the the product improvement and development stages they have to deal with every single product in a different way.

![Figure 81 Layout for electrically powered interlocking](image-url)
In this section, there is an example of a difference in signalling principles between UK and Eastern Europe. The UK case is more advanced, so the Relay and CBI - algorithm has been developed on the more advanced (the UK) application. A layout for electrically powered interlocking in the UK is presented on Figure 81.

The Eastern European version (Figure 82) wouldn’t take overlaps into consideration so train detection units 2T, 4T and 6T would be merged with train detection unit 3T. In Eastern Europe the signalling principles do not allow for any junction route indicators. Also, the distances from the points to the signals could be different (distances not shown on the drawing).

The differences in signalling arrangements on Figure 81 and Figure 82 seem to be very little and trivial, however, they are significant from the train operations and signalling system perspectives. It is important to distinguish the differences.

![Figure 82 Eastern European layout for electrically powered interlocking](image)

On Figure 81, signal S1 is equipped with a junction route indicator that is represented by a single line above the green aspect circle. The legend details the signal S1 description. On Figure 82, the junction route indicator of signal S1 has been removed as the Eastern European signalling principles do not define such indication and a usage of the junction route indicator is not allowed.

Analysing the algorithm of electrically powered interlocking and the pre-selection sequence of the algorithm presented on Figure 25, it can be seen that the condition Are the tracks 2T, 3T, 4T and 5T free? (Conditional step XVII) will not work for both cases of the UK and Eastern European signalling arrangement. It is therefore important to replace the question with the following: Are the tracks of route S1->N free? (Conditional step XVII) so that it works in both cases.

The modified route pre-selection sequence will look like the one on Figure 83.
In terms of junction route indicator differences between signalling principles in the UK and Eastern Europe, the Relay and CBI interlocking algorithm in its sequence Displaying a proceed aspect for a train on signal S1 talks generally about a proceed or red aspects. A junction route indicator will be part of a proceed aspect, so from the formalism perspective it consistently takes into consideration and implements both cases.

The algorithms have been tested using various signalling principles applicable to railway junctions in the following countries: Australia – NSW, QLD and VIC, the UK, Eastern and Western Europe as well as America. Those formalisms are confirmed working for all those cases.
Developing formalisms in such a way that provides consistency and allow applications of various signalling principles and various technologies leads to the development of new signalling concepts based on the same formalisms as well as implementation of intelligent transport functions in concurrent processing.

9.5.6. New technology applications

Introducing consistent formalisms that can be applicable to all signalling principles is important as it leads to potential technology consistency in the future.

In Europe, the idea of introducing The European Railway Traffic Management System (ERTMS) and European Train Control System (ETCS) as part of the ERTMS influenced production of various ERTMS/ETCS standards. Unfortunately, those standards provide written principles description without formalisms. In practice there are mutations of ERTMS/ETCS even in one and the same technology provider.

Four interlocking process algorithms (Section 5) provide a wide range of opportunities for testing new concepts of interlockings.

One of the new concepts that would be worth testing is a railway junction in ERTMS/ETCS application. This task has been purposely excluded from this thesis as there is more discussion required around the application. For example, one of the main questions, not answered yet, is the on-board equipment part of a signalling system or this is part of a locomotive? For the currently proven algorithms and treating on-board equipment as part of a locomotive it seems logical to try to implement the Relay and CBI interlocking algorithm while in the case of on-board being part of signalling system the algorithm needs to be modified.

Looking ahead, there may be a completely new concept for signalling a railway junction that provides a higher integration scale of signalling system components that can significantly improve reliability. It could be a new way of moving points, it could a new way to display a signal to the train driver. However, the new technology could be implemented in the same way using interlocking process formalisms. It is crucial that interlocking process formalisms are in place to guide consistent development of the new technologies.

10. Discussions and concluding remarks

The thesis presented a formal method for documenting and evaluating railway junction interlocking and signalling. In doing so, the thesis:

- elaborated on the railway junctions’ operational conditions including those influenced by specific track arrangement(s)
- developed an analytical model to calculate the railway junction’s interlocking and signalling requirements determined by the track arrangement installed, such as:
• minimum travel distance
• maximum velocity
• minimum train travel time in the track arrangement

- built a train travel chart that graphically presents train operations and analysed a rail transportation process and distinguished requirements or selection criteria for railway interlocking (interlocking processing times) in the transportation process

- tested the proposed methodology by elaborating on a practical example – a task of designing/selecting an interlocking & signalling system for a coal transportation process under the given railway junction configuration and its operational constraints

- defined performance measures relevant in the railway interlocking evaluation process, such as interlocking processing time, signalling system cost, interlocking functionality, signalling system availability and reliability. Those measures allowing consistent comparison and evaluation of the interlocking on a railway junction

- included a complementary RAMS technique into the evaluation of railway interlocking as RAMS can simulate the behaviour of the signalling system based on equipment failure rate, train headway (an interval between trains) and signalling system models

- tested the formalisms to signal a railway junction under railway junction differences like: track arrangement with different gauges, electrified and non-electrified railways, self-setting points, hybrid signalling solution, Signalling principles and some new technology applications

- introduced intelligent transport functions with detailed description of functionality, a potential way of implementing into a signalling or/and train control system, and explained those functionalities.

The following conclusions can be drawn:

- Currently implemented types of interlocking are constrained to perform only interlocking functions related to the train operations ensuring those operations are safe. Computer Based Interlocking processing is slow and the addition of new functions can only interrupt computing standard interlocking functions

- All types of interlocking perform a sequential interlocking process. Wherever new technology or/and concurrent interlocking processing are considered there will always be steps in the interlocking process. It is therefore desired to combine the advantages and features of electrically powered interlocking (both relay and computer based interlocking) when seeking a new interlocking process and new technology implementation
• The electrically powered interlocking algorithm would enable the deployment of new interlocking technologies such as automatic train protection with train management system. This technology of signalling system uses electronic interlocking similar to electrically powered interlocking that cooperates not only with signalling components but also with train on-board equipment. For example: European Train Control System (ETCS), Chinese Train Control System (CTCS), Communication Based Train Control System (CBTC) or simplified Automatic Train Protection (ATP) like WESTECT (system designed by Invensys Rail). Those train on-board systems as well as radio communication equipment have to be discussed separately and therefore are excluded from the paper

• Even if the railway junctions’ differences are significant, there is very little impact on standard formalisms of interlocking process. The changes in signalling related to those implementations are only around technology or technology implementation and have no impact on interlocking process formalisms

• There are intelligent transport system functions (like those presented in this thesis) that should be introduced into signalling interlocking process rather than train control process. Obviously, it is critical that wherever possible the interlocking processes the vital functions and non-vital functions (e.g. intelligent transport functions) in concurrent processing rather than sequentially. That minimises the processing time and allows the implementation of more functionality into the process

• Works conducted and documented in this thesis allow future analysis of railway junction implementations in areas like: time of signalling equipment operation, total signalling time to signal a train and cost of technology implementation.

The proposed methodology provides the right level of abstraction for the properties shown allowing consistent comparison of various signalling and interlocking technologies within each interlocking type. The method is directly implementable by the way of following the sequence of steps presented in this thesis and the author hopes the information included in this thesis will enhance the knowledge of transport or signalling planners to be able to propose the interlocking and signalling technology that meets the operational conditions on railway junction.

11. Contributions of this thesis and related publications

The thesis has:

• developed a structured method to enable railway transport planners to evident a specific railway junction arrangement and, in response to it, determined and described corresponding signalling and interlocking algorithm. This has included characterisation of:
• manual interlocking algorithm

• mechanical interlocking algorithm

• electrically powered interlocking algorithm.

• developed an analytical model to calculate the railway junction's interlocking and signalling requirements determined by the track arrangement installed, such as:

• minimum travel distance

• maximum velocity

• minimum train travel time in the track arrangement.

• defined performance measures relevant to the railway interlocking evaluation process, such as interlocking processing time, signalling system cost, interlocking functionality, signalling system availability and reliability. These operational performance measures allow consistent comparison and evaluation of the interlocking on a railway junction.

It is believed that this thesis is the first of its kind which offers a formal method for consistent and comprehensive comparison of signalling and interlocking technologies from the viewpoint of the specific railway junction operational requirements and performance measures.

The following papers have been published/submitted for publishing by the time of writing this thesis:


12. Further research

This chapter provides an indication of what would be a specific area that needs further development in the formal method delivered in this thesis.

This thesis elaborates on the interlocking processes on a railway junction located on a single, bi-directional railway. Following the methodology defined in this thesis, there is a need to further extend the formal method to be able to find requirements for interlocking to be implemented at railway stations, on multiple track arrangement and on level crossings.
The evaluation methodology could potentially remain unchanged, however, the steps of interlocking process algorithms would need to include a more sophisticated approach to be able to calculate the interlocking processing times. The way of calculating functionality in those cases should be also reviewed.

12.1. Intelligent transport system functions

Nowadays we can observe the tendency to implement more and more functionality into the transport systems. This is to make the transport more user-friendly and also more intelligent so that some unwanted human factor is eliminated.

Rail transport is always at the end in terms of innovation and is more proactive toward safety, reliability and availability. Currently it can be observed that rail transport accommodates more and more systems that are independent from signalling or control technology and processes. Those systems usually do not have any direct input to the signalling and control system technology. In some cases, it is crucial to include some output from those systems to safety related technology to provide more intelligence. Below, there are a few examples of systems that could be used to make signalling and control systems part of intelligent transport systems.

12.1.1. Points condition monitoring

Currently implemented types of interlocking are constrained to signalling intelligence only and even more to the signalling intelligence relevant for the interlocking process, e.g. in the electrically powered interlocking there is a function of checking lamp filament or/and LED module before the proper proceed aspect is given to the train driver but for example if a problem is detected the interlocking logic will not re-route the train earlier so that potential train stop can be eliminated.

One more interesting example is when points operation starts showing some problems that are not yet stopping a train but if not attended by maintenance finally will cause the points to fail. Also in this case various technologies of interlocking logic currently implemented do nothing to re-route the train or inform the driver to slow down.

Figure 84 An abnormality in points machine operation [53]

Figure 84 shows a print screen of a points condition monitoring chart for a particular operation where the system highlights abnormalities in the points operation at the
locking phase. The points have been finally locked and the interlocking didn’t highlight any abnormal behaviour to the control system. In this case the potential cause of this abnormality could be the claw lock out of adjustment or an obstacle located in between the points blades that has been crushed in 0.2 seconds. The system clearly highlights that someone could call the points again straight after the alarm and train passage to seek a similar chart. If the chart is normal it means there was an obstacle causing a temporary problem and a message should be passed onto maintenance that at the next visit it would be good to clean the points of any potential obstacles.

On a single railway junction the opportunities to equip interlocking with some intelligence that comes from point condition monitoring are limited, i.e. a stand-alone points condition monitoring system provides enough intelligence to inform the maintenance crew about potential problems on the turnout but in those places where train re-routing is possible to achieve (especially in suburban areas) it would be desired to equip the interlocking with some kind of intelligence that uses preventive maintenance systems as an additional input in the interlocking logic decision making process. Looking at the track layout from the example on Figure 85 two railway junctions can be distinguished that are part of the same station track layout but can route a train in different ways to finally travel from the station in the same direction. The train can therefore be re-routed if there is a problem or a potential problem in changing the points position from Normal to Reverse.

![Figure 85 Schematic of a railway station track layout](image)

Looking at the example from points condition monitoring above (Figure 84), a simple condition in the route pre-selection part of interlocking algorithm could re-route the train from travelling to Platform 1 to travelling to Platform 3. That operation will also require interlocking logic to cooperate with intelligent passenger information system.

### 12.1.2. Delaying train when necessary

It is crucial that the re-routed train will wait on the passengers and not create unnecessary pressure on passengers to run to Platform 3.

The situation could lead to safety issues and definitely does not take into account people with disabilities.

Applying some techniques to calculate or estimate up front the time of moving the passengers from Platform 1 to Platform 3 for all type of passengers and including
those calculations into the intelligent passenger information system to compare the time with the time calculated for the approaching train, the intelligent transport system feature could provide some input into the interlocking to slow down the train on the way to Platform 3. In such a way, the train will get to the station avoiding the points fault, the passengers will be able to move from Platform 1 to Platform 3 on time without safety issues, the train will not be completely stopped, just slowed down so the energy necessary to run the train will be optimised.

12.1.3. Interlocking processing time and passenger information system

At the performance level, one perhaps surprising, feature of Computer Based Interlocking (one of electrically powered interlocking) is their low speed of operation. This results from their serial processing architecture compared with the parallel processing structure of a relay interlocking, which enables them to carry out several operations at the same time. This ability makes relays particularly suited to densely trafficked sections of line where throughput needs to be maximised. [54]

It is therefore extremely important that railway junction interlocking process formalisms process sequentially the only safety critical steps and other relevant functions are concurrently processed within technology implementation equations (ideally in concurrent processing) giving input to or/and receiving output from the core interlocking process.
References


[53] Points Condition Monitoring by Strukton (www.strukton.nl), printscreens from real Queensland and Western Australia implementations of the system monitoring Siemens (former Invensys Rail, former Westinghouse) points machines M23A, 2013.


