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Hardware-in-loop based performance evaluation of Fixed block and Moving block signalling systems in railway traffic management

Tesi di Laurea Magistrale in Mobility Engineering

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Abstract

With the modernization of railway signalling systems as the European Rail Traffic Management System (ERTMS) framework, there are a lot of improvements that have been brought to the safety, interoperability and operational efficiency of the European railways. The European Train Control System (ETCS) facilitates the process of shifting from the traditional Fixed block signalling towards more progressive Moving block and continuous supervision systems. This thesis will provide a performance comparison between the principle of Fixed block and Moving block signalling in the conceptual and functional structure of ETCS.

The MATLAB-Simulink® modular simulation environment has been utilized to simulate longitudinal train dynamics, braking curve oversight, movement authority production, and driver behavioural reaction in line with the logic of ETCS functions. It was introduced as a two-train scenario (one leading and one following) to determine the performance of the system under the same infrastructure constraints, where the maximum allowed speed was 160km/h and a nominal headway of 240 seconds. The framework was also extended to real time validation by integrating a Raspberry Pi® platform and using UDP-based communication to create a hardware-in-the-loop(HiL) test bench.

The key performance indicators were obtained directly out of simulation results, such as motion regularity, commercial velocity, and effective line capacity. Findings suggest that, the supervision of Moving blocks in an ETCS-based logic is much more effective in terms of efficiency of operations. The regularity of motion of the trailing train further rose with the Fixed block conditions to Moving block operation and commercial velocity rose by around 8%. Moreover, the dynamic separation led to less effective headway at terminal arrival to prove significant increases in practicable line capacity potential.

The results validate the fact that changing the discrete infrastructure-based block segmentation to the continuous braking-curve-based supervision as envisaged in the ERTMS/ETCS evolution improves the utilization of the infrastructure without reaching the maximum speed allowed. The simulation structure developed is a scalable interface to use in the future to actual railway corridors as well as be integrated with industrial real-time validation systems.

Keywords: ERTMS, ETCS, Fixed block signalling, Moving block signalling, UDP, Raspberry Pi®, Hardware-in-the-Loop test bench.

Summario

Con la modernizzazione dei sistemi di segnalamento ferroviario nell'ambito del Sistema europeo di gestione del traffico ferroviario (ERTMS), sono stati apportati numerosi miglioramenti alla sicurezza, all'interoperabilità e all'efficienza operativa delle ferrovie europee. Il sistema europeo di controllo dei treni (ETCS) facilita il passaggio dalla tradizionale segnaletica a blocchi fissi a sistemi più avanzati a blocchi mobili e a supervisione continua. Questa tesi fornirà un confronto delle prestazioni tra il principio della segnaletica a blocchi fissi e quello a blocchi mobili nella struttura concettuale e funzionale dell'ETCS.

L'ambiente di simulazione modulare MATLAB-Simulink® è stato utilizzato per simulare la dinamica longitudinale del treno, la supervisione della curva di frenata, la produzione dell'autorità di movimento e la reazione comportamentale del macchinista in linea con la logica delle funzioni ETCS. È stato introdotto uno scenario con due treni (uno in testa e uno in coda) per determinare le prestazioni del sistema con gli stessi vincoli infrastrutturali, dove la velocità massima consentita era di 160 km/h e l'intervallo nominale era di 240 secondi. Il framework è stato inoltre esteso alla validazione in tempo reale integrando una piattaforma Raspberry Pi® e utilizzando una comunicazione basata su UDP per creare un banco di prova hardware-in-the-loop (HiL).

Gli indicatori chiave di prestazione sono stati ottenuti direttamente dai risultati della simulazione, quali regolarità del movimento, velocità commerciale e capacità effettiva della linea. I risultati suggeriscono che la supervisione dei blocchi mobili in una logica basata sull'ETCS è molto più efficace in termini di efficienza operativa. La regolarità del movimento del treno in coda è ulteriormente aumentata con il passaggio dalle condizioni di blocco fisso al funzionamento a blocchi mobili e la velocità commerciale è aumentata di circa l'8%. Inoltre, la separazione dinamica ha portato a una riduzione dell'intervallo effettivo all'arrivo al capolinea, dimostrando un aumento significativo del potenziale di capacità praticabile della linea.

I risultati confermano che il passaggio dalla segmentazione discreta basata sull'infrastruttura alla supervisione continua basata sulla curva di frenata, come previsto nell'evoluzione dell'ERTMS/ETCS, migliora l'utilizzo dell'infrastruttura senza raggiungere la velocità massima consentita. La struttura di simulazione sviluppata è un'interfaccia scalabile che potrà essere utilizzata in futuro per i corridoi ferroviari reali e integrata con sistemi di validazione industriale in tempo reale.

Parole chiave: ERTMS,ETCS, blocco fisso, blocco mobile, banco di prova Hardware-in-the-Loop

Contents

1 Introduction

Railway signaling systems rely on a synchronized system of hardware and software to make sure that the flow of trains is regulated in a safe and efficient manner. The railway traffic management systems of the present day are based on the high signalling architecture to ensure the safety, capacity management of the line, and the dependability of the operations. Traditional Fixed block signalling breaks up the railway infrastructure into predetermined blocks on the track and only one train is allowed to be in a block at a given time. Though this is safe in nature, it restricts the operating flexibility and capacity of operations, especially on busy corridors. The development of principles of Moving blocks, which are introduced through the schemes of ERTMS/ETCS, brings about dynamic separation of trains, which is conducted on the basis of real-time position, braking capabilities and safety margins, as opposed to physical blocks (Barbaro, 2021). This shift is a radical change in protection logic based on infrastructure to that based on trains.

Safety wise, improved signalling systems are effective in lessening the reliance on the visual interpretation of trackside signals by the driver. In traditional systems the visibility of the signal can be affected by the weather, curvature, velocity or human error. Systems based on ETCS send information related to the signalling directly to the cab of the driver and allow maintaining constant control of the speed limit, braking curves, and movement authority. This helps to remove ambiguity to the interpretation of signals and to automatically intervene should safe braking profiles be violated. As a result, incidences of overspeed and signal-passed-at-danger (SPAD) are reduced significantly.

Radio Block Centre (RBC) is the major part of this architecture. It acts as the decision making unit, which calculates and transmits the Movement Authorities (MA) to the trains, depending on the track occupancy, route availability and operational constraints. The RBC maintains safety margins by ensuring dynamically the safe separation distances between trains, which guarantees maximum infrastructure use.

This real-time communication between the train and RBC in Moving block configurations gives an opportunity to reduce the headways in order to improve the commercial velocity and the total capacity of the line without affecting the impaired safety.

The move to a Moving block signalling system as opposed to Fixed block signal system is therefore not a technological improvement as such, but an evolution in the railway traffic management system. It combines real-time monitoring, automatic handling of safety and dynamic separation logic, which leads to greater efficiency in operation, better driver support, and infrastructure performance. In case required occupancy is not able to be confirmed, special indicator intervals are applied to indicate denial of authority. The internal logic of the RBC works based on the clearly defined states: waiting when requested blocks are not available, using the block when the authority is granted, releasing the block when it is released, and terminating when no additional movements or allocations are necessary.

The various signalling strategies that can be used to implement railway traffic control are characterized by safe separation between trains. Some of the oldest systems are Fixed block (FB) and Moving block (MB) signalling systems. Although they both strive to ensure safe separation of trains, they differ in their basic operational principles, dependence on infrastructure and implications on efficiency.

Fixed block signalling systems are where the railway line is partitioned into discrete track sections called blocks. Every block corresponds to a secured part of the infrastructure which can only be used by one train at the time. Separating trains is hence accomplished by regulating entry to these established physical divisions. Track circuits or axle counters are used to detect the occupancy status of every block, and the occupancy status is indicated to the drivers by visual colour-coded signals along the track (Morten P.Lindegaard, 2000). Under a conventional three-aspect Fixed block system, signalling logic would often be specified as follows: red means that there is an occupied block ahead of the train, which must stop; yellow means that there is an unoccupied block ahead of the train, so the train must slow down and be careful; green means that there are at least two clear consecutive blocks ahead of the train, and the train can proceed normally. It is important to note that this colour coding is a reference to a three aspect system. More complex Fixed block designs can also use four or more aspects, with other intermediate signal states and speed control instructions added. The basic principle however does not change in any way: train separation is controlled by predetermined sections of infrastructure and a signal aspect only varies in case of physical block occupancy status.

Moving block signalling systems, by contrast, do not require the existence of predefined partitions into block sections, but instead calculate safe separation on a dynamic basis. Instead of using predetermined track segments, the safe distance of the trains is determined dynamically and is computed on real time parameters of train speed, braking performance, acceleration properties, gradient profile, and the environmental condition. The logic is generally applied in ERTMS / ETCS Level 2 or Level 3 systems, when constant communication between the train and the Radio Block Centre (RBC) facilitates transfer of revised Movement Authorities. Moving block systems in contrast to Fixed block systems, where the aspects of signals do not change until a trackside detector makes a state change. Moving block systems rely on continuous real-time communication between trains and infrastructure. Consequently, train headways can be optimized whilst keeping a safety margin based on real braking curves as opposed to a conservative segmentation of infrastructure (Vahid Ranjbar, 2022).

The difference between Fixed block and Moving block strategies thus is that safe separation has a different definition: the former one is a discretized infrastructure-based one, and the latter is a train-based and dynamically calculated one. This structural distinction has a direct impact of capacity, commercial velocity, and motion regularity, which constitute the analytical basis of the current thesis. The difference in functionality between the two approaches requires a systematic approach in the dependability analysis of railway services when considering signalling systems and limitations.

Figure 1.1: This represents the basic functioning of a signalling system in train distancing and braking curve design. In particular, Figure 1 (a) concerns FB approaches, while Figure 1 (b) refers to MB signalling systems.

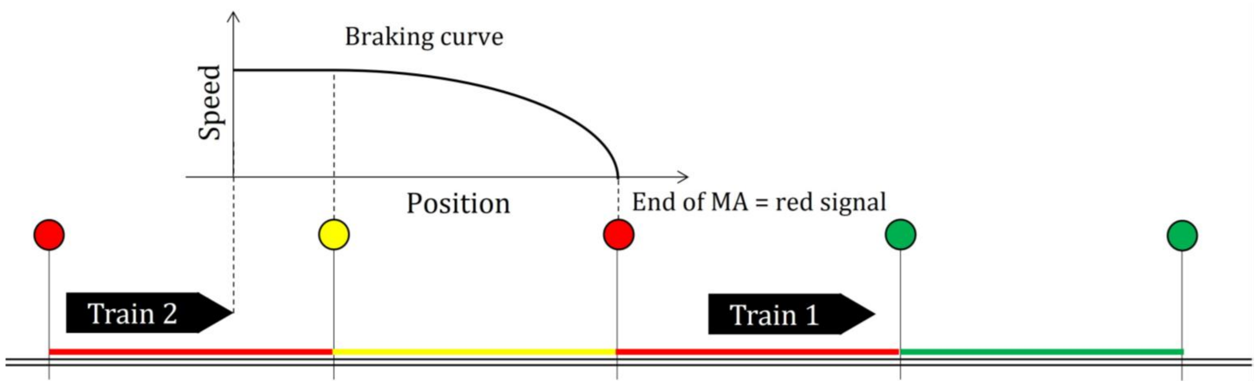


Figure 1(a): Fixed block Signalling System. The red dots and lines represent the states of the Fixed blocks; if the second enters a yellow-signaled block, it must follow a prescribed deceleration curve.

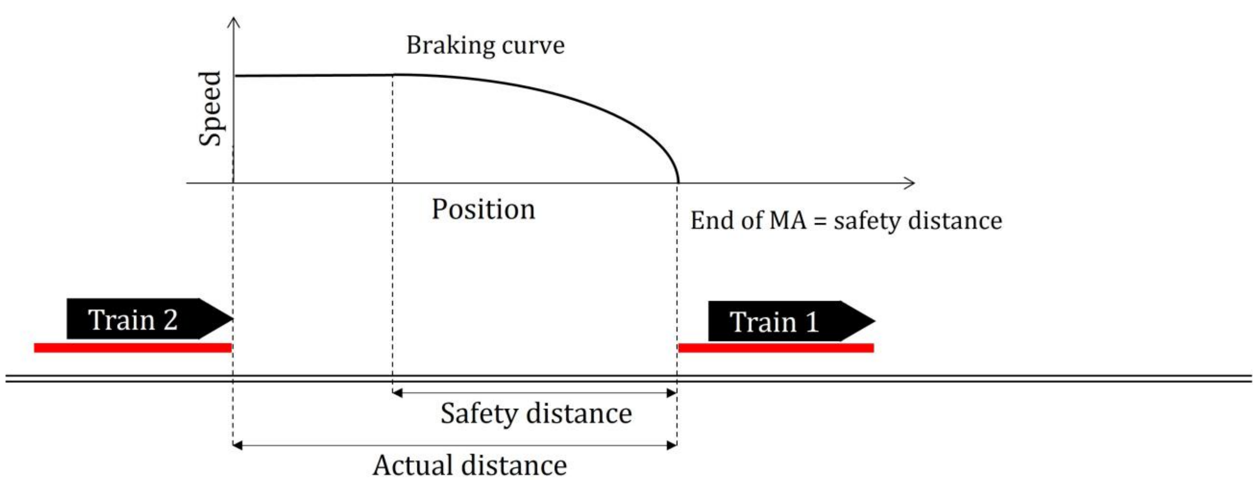


Figure 1(b): Moving block Signalling System. The red lines represent the occupation zones of the trains. If the second train violates a safety distance with the occupation zone of the second one, it must follow a prescribed braking curve.

The current thesis is not concerned with the construction of a simulation platform, but with its systematic use in the evaluation of the performance of railway signalling strategies. Hardware in the loop (HiL) test bench is used to replicate realistic conditions of operation and combine virtual railway models and physical units of computation. The simulation environment is run in conjunction with a real-time target machine (Speedgoat(r)) and some chosen communication and signalling functions are put onto a Raspberry Pi(r) platform. This distributed structure allows the simulation of real-time data transfer between infrastructure control logic and train dynamics, and thus, necessary behaviours of a Fixed block and Moving block signalling system can be reproduced within a controlled experimental system.

With this HiL setup, the two signalling approaches are tested under the same operational conditions so as to measure the difference in their performances. The analysis revolves around the key performance indicators (KPIs) such as Line Capacity (LC), Motion Regularity (MR) and Commercial Velocity (Vcomm). The study is conducted using comparative simulation campaigns to determine the effects of structural differences between fixed and Moving block control philosophies on safety margins, headway management, use of infrastructure, and the overall performance of the operations.

2 State of the Art

2.1 Historical evolution of railway signalling

In the early stages of railroads developments, visual signs (either flags or lamps) were manually operated to tell train drivers to move or stop. Such primitive arrangements were, to a great extent, reliant on the mindfulness of the personnel and as such could not be trusted during low visibility conditions, and could not guarantee high levels of traffic capacity. With the growth of railway networks and train frequency, the development of more systematic signalling processes was observed due to the growth of accident risk, for example with the employment of automatic semaphore signals, leading to the formalization of Fixed block(FB) signalling. Nevertheless, the FB approach became evidently inefficient with an increase in the speed of operation at the end of the 19th and early 20th centuries. The necessity of controlling train movement with discrete block sections limited the achievable traffic capacity, and made the system unsuitable to respond to further demand increases. As a result, several refinements were made, the most prominent one being the interlocking systems. Its functions is the avoidance of conflict in track reservation and utilization in the of junctions by making points (switches) and signals incapable of being set inconsistently. It was also during this time that track circuits were introduced so that the presence of a train in a block section could be detected automatically.

The replacement of purely mechanical components by electronic systems started in the middle of the 20th century and has gradually given way to signalling that was no longer manual or semi-automatic and instead centralised on electronic interlockings. The subsequent advances paved the way to a computer-based control system for railway operations, in which one hub would manage large areas of the network. Technological advances were motivated by the trade-off between the need to guarantee the safety of the operation and the fact that greater and greater capacity utilisation was required. However, despite this new level of electronic interlocking, traditional Fixed block logic was still constraining the efficiency of railway operations by fixed operating with line sections of fixed length, as determined by infrastructure and not by the train performance. ERTMS Level 0 is the simplest operational scenario where the ETCS-equipped trains pass through tracks that are not equipped with ETCS trackside equipment. Under this arrangement, the train supervision system goes active on board but there is no movement authority transmitted track-to-train. The train is basically controlled through the traditional national signalling systems and ETCS is just an overlay monitoring.

On a network basis, Level 0 offers interoperability readiness but does not add much capacity enhancement. Operation headways have not improved due to the fact that movement authorities continue to use traditional Fixed block infrastructure with trackside signals. The key advantage on this level is the safety monitoring and harmonization of the fleet instead of improving infrastructure performance. That is why Level 0 does not influence line capacity significantly but helps to gradually migrate to higher levels of ERTMS.

Level 1 ERTMS involves the use of trackside balises, which relay the signal data into the cab of the driver. Speed supervision and movement authority is now electronically transmitted although physical trackside signals are usually still used. It is still based on Fixed block separation of trains, although onboard braking curve protection is improved (LC, WC, SBI, EBI).

Maybe the most important effect is the network impact because Level 1 is much safer because it minimizes the reliance on visual signal interpretation on the part of the driver. Automatic intervention is used to mitigate the effects of overspeed conditions and Signal Passed at Danger (SPAD) events (Vahid Ranjbar, 2022). Capacity gains are however usually constrained as separation logic is infrastructure based and block oriented. This is due to the fact that most improvements are associated with the reliability of operations and low reaction time, and not structural increment of throughput.

Level 2 ERTMS is a great change in signalling philosophy. It also removes the use of trackside colour light signals and also provides constant radio communication between the trains and the Radio Block Centre (RBC). Movement Authorities are the dynamically computed and sent through GSM-R or other similar systems and real time monitoring of speed and position is achievable.

Though Level 2 is still capable of running on the principle of Fixed blocks, it forms the technological basis of more progressive dynamic separation methods. Continuous communication enables the management of headway more efficiently, block release to be faster and infrastructure to be utilized better. RBC plays a primary role of decision making, including route allocation, calculation of movement authority and monitoring of safety margin using real time data.

Regarding network performance, Level 2 will offer quantifiable capacity and commercial velocity improvements, especially in high-density corridors. Operation is more flexible and perturbation recovery is more efficient by eliminating the need to depend on trackside cues, and allowing ongoing supervision.

Whereas the operation of Moving block is commonly linked to Level 3 of ETCS, Level 2 defines the communicational and control framework needed by dynamic separation logic. Moving block strategies are based on the Level 2 philosophy (J.A.Koning, 2021) that leaves the predefined block segmentation and computes safe braking distance in real time.

Regarding this thesis, it may be conceptually equivalent to the replacement of infrastructure-determined separation (Level 1/2 Fixed block logic) by train-centric dynamic supervision facilitated by higher-level ERTMS architectures. As passenger and freight demands increased at the turn of the 21 st century, solutions needed to be made to address these limitations via Moving block concepts through modern signalling architectures including those that are outlined within ERTMS/ETCS Level 3. Instead of dividing the line into blocks of fixed length and location, Moving block systems compute a real time calculation of the minimum safety distance between trains, taking into account their speed, break capabilities, and communication reports obtained by the control centres. The switch enables more track capacity as the absolute distance between the trains can be reduced, without violating the safety protocols and regulations. This involved a combination of constant position reporting by means of onboard units and centralised Radio Block Centres (RBCs).

This change in technology from Fixed block to Moving block was supported by the improvement in telecommunication and computing power that helped to improve the real-time localization of train at large scale. Onboard sensors were enhanced, and satellites with digital radio links like GSM-R, and enhanced fidelity in transmissions of positional data. This was a paradigm shift in history in which the primary enforcer of safety was formerly physical infrastructure by creating a physical barrier, but now is a calculated envelope to adapt the live operating environment. A similar line of the history of this process has been the gradual formalisation and standardisation of signalling protocols. The practises of local railway companies, which began as localised ones, became nationalised and finally suggested harmonised European standards in projects such as ERTMS. This standardisation not only enables cross-border operations but also prepares clear standards on which innovations such as virtual coupling, which is the conceptual descendant of Moving block principles can be experimented in terms of dependability characteristics within definite boundaries of uncertainty. The other historical pattern that is worth noting is the intersection of signalling solutions with larger operational modelling activities over the years. Unlike the previous designs where early designs came into being through trial and error designs based on on-site experience, the contemporary designs are more dependent on predictive simulation platform without undertaking any form of field deployment. Complex architecture prototyping in Hardware-in-the-Loop is now routinely done before actual track installation, the progression of which is both an advancement in technological capability and an increase in regulatory pressure to fully test safety claims before they can be publicly operated. Following this cycle shows a cyclical pattern: safety issues leading to initial innovations, efficiency issues causing development, communications technology making fundamentally new paradigms and simulation-based validation placing the gap between theoretical gain and operational proof-of-concept. Every stage represents a compromise between upholding security margins against unexpected occurrences and pushing the boundaries of capacity as far as data and regulatory provisions will allow. It seems probable that the developments in the future will only enhance this trend and not destroy it completely. Moving block logic is already being extended in the same way forward, including with direct train-to-train communication, which is under exploration, in addition to being used with satellite-based positioning additions. This is indicative of an evolutionary continuity based on historical lessons which preserve the fundamental philosophy of safety, but changes its implementation mechanics as its technical resources and transportation needs are adapted to existing conditions with changes in time.

2.2 Conventional Fixed block signalling principles

The principle of Fixed block signalling is that a railway line is divided into fixed-block track, each block being identified by a known set of track sections, which are occupied by detection signals. A block can only be occupied by a single train at a time and this is the main protection against collisions. These blocks are deployed physically or virtually to provide a separation of the trains that is unintentional, and overlaps do not happen even in case of operational errors. In one such system, block occupancy status is converted into signalling information that is sent to drivers, traditional implementations are based on visual indicators mounted along the line, and the current one incorporates automated train detection through track circuits or axle counters. Operationally, every block is constantly patrolled by monitoring its status, occupied or free, to other trains. The control logic imposes the rule that a train can only enter into an empty block once it has been cleared through the signalling system. This clearance is now implemented by the more modern Fixed block designs as Movement Authority (MA) messages translated into both the fixed speed limits that can be obtained using the corresponding static and dynamic profiles of the section in question. Ma transmission may take place using physical signals in addition to the track in traditional systems or using digital communication connexions like GSM-R when incorporated in the sophisticated systems of ETCS Level 2. This digital improvement is the existence of Fixed block logic but it allows constant updates provided by a Radio Block Centre (RBC), which is more responsive than older relay-based networks. In spite of these implementations, the inherent weakness exists, the blocks are fixed and their size is not adjusted to the real performance of the trains or the current conditions.

This implies that the separation between trains is not determined by the operational requirements in real times but it is determined by the boundary set by the infrastructure. Fixed block signalling does not allow a following train to safely reduce headway by means of a better braking capacity, or good track conditions. Section 2.1 brings out the effect that this limitation had in triggering subsequent interest in Moving block concepts. Nevertheless, in a Fixed block operation, there are certain benefits that should be mentioned, train spacing predictability eases the traffic scheduling and compliance with interlocking regulations at junctions. How Fixed block principles are applied to colour-coded signalling also demonstrates the principle further. Each section occupancy may be presented in a number of ways, such as red for occupied immediate next block, yellow for one free block ahead and green for two free blocks ahead (Morten P.Lindegaard, 2000). With these distinct gradations, drivers can make time adjustments to the speed and distance without processing complex data streams of numbers. These visual signals though deterministic in nature provide effective situational awareness in situations when the driver has to respond quickly to the changes. However, it should be remembered that the design margins inherent in such colour states, which are frequently founded on worst-case assumptions regarding the braking distances, can result in capacity potential that will not be realised in high-performance corridors on the rail.

The Fixed block division is also in heavy interaction with safety subsystems such as automatic train protection (ATP). Since ATP implements compliance to authorised speeds in some areas, the conversion of MA to restrictive braking curves coincides well with set block occupancy regulations. In case it is an emergency situation pre-established brake curves are used to make sure that even in case of sudden stops, the train does not run into a neighbouring section where there is somebody. Such parameters as maximum emergency brake distance are incorporated into system logic to ensure that there is no overlap between operational envelopes of successive trains. Such conservatism guarantees security but may decrease production or efficiency when different trains possess different braking forces, but have the same separation margins, due to infrastructure design and not due to dynamic capabilities. Modelling-wise, to simulate Fixed block performance, it is necessary to assign discrete occupancy states to the subsequent track sections with time and calculate transitions as trains pass through them.

In more abstract forms of representation, such as discrete event systems based on detailed models written in MATLAB-Simulink®, the focus on continuous dynamics is replaced by the state change events of block becomes free or train enters new block. The occurrences spur reliability assessment techniques applicable in comparison to other architecture. The parameters that are inputted into these simulations are constant limits on speed in sections, braking functions that depend on the characteristics of rolling stock, and environmental modifiers like change in friction due to weather changes. Fixed block principles can be used together with digital communication protocols, when combined with ETCS Level 1 or Level 2 layouts, but still use physical segmentation as a safety integrity mechanism. At Level 1, the data statements contained by balise transmissions are only updated on the passing of particular trackside points. Level 2 constant MA transmissions carry on through GSM-R interconnection between RBC and onboard apparatus but still utilises fixed spatial blocks to determine permitted ranges of movement. Under Level 2 of train positioning, the status of occupancy is determined by track circuits or axle counters, which are entirely consistent with the conventional philosophy of Fixed block control though modern transmission technology has substituted parts of field hardware. Fixed block signalling has an indirect effect on the effects on energy consumption, since the opportunities to accelerate, with respect to traction are limited by the distance between sets, prior to reaching a restrictive aspect.

On down-grade slopes on which regenerative braking may yield significant energy savings, restraining signal spacing occasionally results in prolonged coasting instead of active regeneration until it is allowed to join it again in the next blocks. On the other hand, long uphill gradients frequently require sustained full throttle application because of long approach ranges before reaching stations or junctions, once again illustrating the interaction between infrastructure specified segmentation and energy management regimes regardless of the abilities of rolling stock. In a scientific perspective of summarising this principle of operation, it is seen to have a perennial value, as well as its limitations, being simple to implement and integrate with the existing interlocking principles, it is trustworthy in its application in a wide range of infrastructure generations. The cost of rigidity in spatial segmentation however limits the maximum capacity increment and efficiency enhancement compared to the communication-based offshoots. Any comparative performance analysis should consider these structural limitations together with possible benefits that can be gained in case of hybridization experiments with fixed and Moving blocks working in harmony under controlled simulation condition.

2.3 Emergence of advanced signalling concepts

The constraints of the traditional Fixed block operation have been steadily stimulating the transition to signalling architectures, which dynamically adjust separation criteria depending on the operational conditions. The change has come with the heavy improvements in telecommunication, train localization precision, and level of processing power of the trackside and onboard subsystems. Early European projects like ERTMS/ETCS attempted to substitute a collection of national systems that could not be linked into a standardised system incorporating safety logic, exchange of real-time data and operational planning layers. GSM-R integration offered a standard communication platform, which facilitated continuous communication between Radio Block Centres (RBCs) and trains. This framework combined with European Tool Machine Language to manage traffic permitted the use of more sophisticated control methods in which decision-making could be informed by real-time traffic information instead of being based on timetables that were purely pre-determined. Moving block principles apply one of the most visible innovations in this wider category. Instead of the fixed geographic segmentation, the system computes a dynamic safe zone of each train depending on the speed and braking capabilities, gradient, adhesion, and communication intervals. With RBC-OBU exchanges updating these parameters constantly, trains can run nearer to their leaders with no violation of safety margin.

According to Roberto Nardone (Joelle Aoun, 2024), the studies on ETCS Level 3 and CBTC Moving block form are part of a broader agenda that encompasses the concepts of the future like virtual coupling, with the separation distances potentially being minimal, and coordinated control regimes. Even though Moving block in itself is a qualitative innovation as compared to Fixed blocks in its capacity capability and flexibility, the implementation of the Moving block needs a lot of modelling before it can be physically implemented. Dependability qualities, availability, as well as safety integrity levels and performance should be considered stringently through model based techniques, and according to standard benchmarks. Methods such as Petri Nets or Timed Automata are useful in modelling simultaneous activities and chance events that influence regularity of the system. By adding time uncertainty to simulation models already adopted by institutions such as POLIMI (Barbaro, 2021), the researcher is able to identify variables the unpredictability of which has the greatest impact. These results are used to refine operational rules as well as hardware specifications of rolling stock as well as fixed installations. A new development in the contemporary signalling measurement is the combination of capacity analysis with economic sustainability indicators and the environment. Checking exercises assure that the majority of modern assessments utilise simulation devices or operations research techniques, optimization of timetable is especially critical, to measure the effects on the output. There has been increasing interest in stochasticising these models to have a more realistic representation of real-world disturbances such as smaller technical failures or delays caused by passenger flows. This enables higher principles like Moving block to be evaluated not only on the perfect theory of its operation but also on the stability of its operation under deteriorating conditions. The trend of more advanced assessment systems can also be seen in multi-layer simulation systems.

To illustrate, macro-level models will make general evaluations of the line performance in different situations with different capacity limitations and sustainability objectives. DES concerns the effect of uncertainties on availability, high-fidel dynamics simulation of vehicle dynamics models the interaction between longitudinal train motion and signalling logic on a sub-second time scale. The interaction between layers is especially significant in the context of transferring the result between scales as the macro models may be able to decide on reasonable headway targets that can be tested with micro-level simulations with actual braking curves and communication latencies. More confidence comes with advanced signalling designs through practical experimentation platforms like Hardware-in-the-Loop (HiL) benches, which combine simulation components with physical hardware components. Architecture can allocate major functions among various machines that are connected through protocols such as UDP, such that, an OBU process can be implemented in Raspberry Pi® codes and other codes in MATLAB-Simulink®. Such a mixed environment allows to prove the interoperability requirements of ETCS SUBSET-026 to dynamic field-like conditions, without operational risk. Cases where hybrid operation is necessary, where the sections of the Moving blocks are interlaced with conventional Fixed block stretches are of special interest as they reflect most of the predicted transitional cases in rollout. In these circumstances the signalling system has to be able to fluidly transition between distance envelopes under the advice of dynamic calculations to inflexible segment limits without ceasing continuity of issues of movement authority. Surveys in the field of literature, dedicated to the preparation of railways in case of the introduction of Moving blocks, show that the quantitative standards of such hybrid areas do not only address the change in railway capacity, but also safety indicators and tools of the ecological performance investigations.

These transitional dynamics will have a direct impact on infrastructure investment policies because introducing more advanced concepts can be phased in, and not necessarily converted into a network-wide conversion. In the operational perspective, the development of the sophisticated signalling concepts can be regarded as the change of the centre of control that is not based on the infrastructural limitation but on the information-based flexibility. Where the traditional systems have placed their safety margins on physical geography in fixed segmentation, the modern methods place them on real time computation that is updated on the basis of constant measurement. This requires a higher confidence in making sure that all data entries, position reports, speed readings, braking performance estimates are timely and reliable because misinformation on this part can be immediately reflected in the safe separation calculations. The direction of research indicates further concentration in the choice between travelling block innovations and more radical content like autonomous driving standards of rail guided vehicles.

The critical assessment of this change reveals that even though there are potential benefits of increased capacity utilisation and improved energy use that are observable, as more often as regenerative braking opportunities are used, with adaptive spacing regulations, the reliance on continuous digital communication is a new vulnerability category that does not exist in schemes based on pure physical separation. Glitches in communication, or sensor errors, may readily spread through the control algorithms, unless alleviated by fall-back fail-safe schemes, to a temporary condition of constant block-like protection until regular operation is restored. The higher level concepts of signalling do not build on current practises but re-orient operational priorities on responsiveness and adaptive optimization based on live data streams. This reframing guarantees the greater dependence on validation environments that could effectively recreate disruptions in a realistic manner such that the new vulnerabilities could be revealed prior to service. The trend in the industry seems to be strongly directed toward the implementation of such capabilities in interoperable standards specifications such that a single deployment in one jurisdiction can be fully used in another without a total re-architecture, which is the same objective as the original vision of the ERTMS of unified European railway operations.

2.4 Global trends in signalling modernization

The last 20 years have seen a trend in which a convergence of technology and a performance-based operational concept has been influencing modernization in the field of railway signalling. A large part of this change is grounded in the fact that migration of a Fixed block problem to communication-based solutions that enable finer separation of trains and tighter use of infrastructure capacity has become possible. Although the move block systems have received a lot of academic and industrial interest, their adoption can be seen as a part of larger modernization trends that integrate increased capacity with green sustainability and digital resiliency requirements. As noted in the literature surveys of the last few years, there are a number of rail administrations that have been re-organizing their investment priorities to support signalling architectures that incorporate real-time traffic management, advanced driver advisory functionality, and continuous train localization (Joelle Aoun, 2024). This development seems to be highly intertwined with the macro transport policies with the intention to move the modal share to rail increasing the regularity of services and felt reliability. Here, the use of simulation-based research has gained prominence as not only one of the tools of ensuring safe operation under novel signalling logics but equally, to determine the impact of the same on the output without necessarily incurring preliminary costs of physically implementing the logics. The popularity of predictive models highlights a bias in favor of pre-implementation quantification of benefits and risks, in which models can be stress-tested both in the normal conditions of demand and in conditions of disturbances. The stratification of simulation methods is one of the typical patterns that occur due to these modernization programs. The optimization of macro-level networks emphasizes the way various signalling choices could be in line with the predicted demand curves and investing activity, macro-level operational modelling records headway fluctuations and junction output. Micro-level dynamics are concerned with the vehicle specific braking curves and the acceleration envelopes.

The cross-layered interface enables policymakers to translate the transport objectives at the broad level into hardware or software requirements. As an example, a macro simulation of a possible to minimize headways between 360 sec and 120 sec under Moving block assumes micro validation of realistic latency distributions in the RBC-OBU communications (Barbaro, 2021). Offering reliability cheques, both in the form of safety integrity, availability measures, and performability measures, is increasingly sought worldwide as part of modernization strategies. As opposed to safety verification as a final point after technical deployment, the continuously developing practice incorporates it into an iterative design through model-driven quantitative techniques. The use of stochastic modelling methods to assess the impact of small-scale component failures or communication disruptions spreading across service delivery measures is growing increasingly popular. One of the things that can be seen within this trend is that there is a significant focus on hybrid resilience as the capability of modernized signalling to degrade gracefully to safer, but less efficient states (such as temporarily switching to Fixed block separation when communication paths are cut off) without causing catastrophic disruption. The other trend that can be identified is the association of signalling development with sustainability requirements. The ability to perform continuous control using advanced systems permits the operators to use a smoother speed profile that minimizes unnecessary braking or idling at signals.

Adaptive traffic management modules with train-based control logic have been demonstrated in some pilot deployments to change the departure time by a small amount, to enhance contact flow synchronization along the congested corridors and reduce the peak power to the electrical grid. The inclusion of these features shows that modernization has ceased to be primarily about capacity building, but it is also about ensuring that railway operation is in line with other carbon reduction goals that exist at a national or supranational level. Simultaneously, projects of high-speed rail expansion still influence the modernization trends with the high requirements to the response of a signalling system and the accuracy of the positional update. Even minor delays in the movement of authority data at operating speeds of more than 300 "km/h" can eliminate safety margins unless mitigated by predictive algorithms. It is because of this that some networks in Asia and Europe have introduced experimental train-to-train (T2T) communications structures intended to either be additional or partial replacements to ground-based RBC transmission circuits. These T2T links are expected to build ultra-low-latency coordination channels that will support future operational concepts like virtual coupling at speed that can radically change the flexibility of timetable planning. The commercialization trends that are evident in the world indicate the existence of various modernization archetypes and not just one dominant paradigm. Mature urban metro systems can seek an upgrade cycle where legacy automatic train control modules are replaced progressively with CBTC-based versions and system boundaries maintained. National intercity networks will attempt to focus more on ERTMS/ETCS deployments where transnational interoperability is a strategic priority. Partial Moving block overlay experiment of access points with known bottleneck effects may be attempted along the freight-heavy routes without wholeheartedly replacing the low-density segments. The existence of these differentiated paths tells us that modernization choices are made so that the technological maturity and particular operational situations are matched instead of specifying the same set of prescriptions. The alignment of policies has a regulation role to play.

Presence of harmonized standards like ETCS SUBSET-026 enables infrastructure managers in various countries to determine whether an investment in Moving block technology would be future proof in terms of regional interoperability requirements. Jurisdictions with a weak regulatory convergence can be characterized by diluted modernization processes where proprietary vendor solutions serve small bits of ground without expansion to bigger parts of the ground, a situation, which can defeat economies of scale and inhibit further upgrades. New debates also introduce cybersecurity issues to the limelight as far as modernization planning is concerned. As digital communications have become a part of the safe separation enforcement, the integrity of the authentication and the protection against the presence of spoofed data are no longer negotiable. Encrypted RBC-OBU channels and redundant localization sensors are already part of some projects globally because malicious interference may cause unsafe errors in dynamic spacing algorithms. These advances put security assurance no longer as an auxiliary IT policy but as a component of fundamental safety case validation required ahead of operational roll-out. The speed with which these trends are changing across the globe seems to be dependent on the corresponding cycles of innovation in some adjacent technologies including telecommunications (introduction of 5G into rail applications), satellite navigation augmenting systems with a greater level of positional accuracy, and artificial intelligence approaches to predicting traffic perturbations with references to historical trends. All of them add small steps to the vision expressed by future-oriented operators, highly automated motions of trains coordinated over extensive areas via adaptive algorithms that can react immediately to varying conditions without violating regulatory-acceptable safety envelopes. Collective momentum thus represents a combination of some small-scale retrofit work, much of which goes unnoticed by most and some headline-grabbing pilot projects showing step-change possibilities being run under controlled conditions. It is the crossroad of these strands that constitute the real picture of signalling modernization that is being witnessed in continents today.

3 Performance Evaluation in Signalling Systems

3.1 Definition of key performance indicators

3.1.1 Capacity-related metrics

Railway signalling systems performances can be evaluated with multiple indicators, many of which are related to traffic capacity, measuring the maximum throughput that any section of the rail infrastructure can support within the restrictions of operational and safety limits. In operational modelling these indicators depend on particular physical and operational specifics, such as signalling resolution (block length or Moving block safe distancing), communication update frequency, station dwell time, and rolling stock dynamics. The combination of these factors defines whether there is a constraint in capacity due to track availability or due to operational rules in the signalling logic (J.A.Koning, 2021).

In determining the line capacity (LC) by simulating means, the approach consists in emulating railway operations to evaluate the number of trains that can pass through a particular section per unit of time and still be in line with safety margins. Considering simulation implementing a Fixed block signalling strategy, the calculation of LC in Fixed block systems is based strongly on the block length, which is based on conservative assumptions about braking curve and distances. Setting the block length to be uniform across the whole line heavily reduces the complexity of capacity computation.

Headway is the basic temporal parameter used in the train separation of railway traffic systems. It can be defined as the period separating two trains of passing past the same point along a railway line. In contrast to physical distance-based separation, headway describes the distance using an expression of time, making a direct correlation between the operational safety-related requirements and the line capacity and service frequency. Practically, the distance between trains is defined by the headway, which allows the trains to pass each other without compromising on the safe braking distance and ensuring signalling limits are not violated.

Concerning traffic management, headway is the most important parameter in theoretical line capacity: the lower the headway, the higher the number of trains that can be scheduled within a specific time per hour on a part of the way. But arbitrarily the headway cannot be diminished, since it is limited by the braking performance, signalling logic, communication delays, the gradient condition and the infrastructure segmentation. The fixed block systems are heavily based on the block length (Insaf Sassi, 2023) and signal progression of the signal aspect, which causes a discrete and even conservative time spacing. By contrast, moving block systems permit the dynamically adjusted headway, with the actual safe braking distance being calculated in real-time and could minimize unnecessary time gaps, without sacrificing safety (Barbaro, 2021).

Thus, headway is not a simple scheduling parameter but it is a direct indication of the signalling philosophy and safety architecture used in a railway network. It can be considered the key concept in the performance assessment that was carried out in this thesis because its optimization is a compromise between the capacity maximization and strong operational safety margins.

Green Wave policy is a policy where the coordination of the signal clearance is done such that a train that is passing by is allowed to pass through consecutive sections without unnecessary stops and braking. The aim is to have a continuous and smooth profile of speeds to reduce variation of speeds and maximize on the energy efficiency.

Green wave operation in Fixed Block systems needs to be well coordinated in the timing of block release. When blocks are cleared one just before the following train enters the block, the train will go through a series of green lights, which keeps it moving at a constant pace. However, with the discrete nature of block segmentation, it is not easily synchronized particularly during dense traffic.

Green wave behavior is easier to form in Moving Block systems. Since movement control is constantly updated and braking control is actively calculated, the following train can vary the speed with a fixed change to maintain an ideal separation.

The comparison of the two considered (varying) and standard (static) Fixed block lengths adds depth to the analysis as the maximum yields a more conservative measure of the analysis, which can be attributed to safety priorities, and the minimum to the efficiency-oriented measurements (Joelle Aoun, 2024).

Focusing now on the evaluation of the capacity-related performance indicators in scenarios with Moving Block signalling, spatial abstractions with the temporal headways that are calculated by the dynamically recalculated safe separation distances. In this case, the metric is sensitive to communication delays between RBCs and OBUs. A doubling of the updating cycles of 1 to 5 could be enough to expand the calculated lengths of safe zones to cause the lengths of achievable headways to change considerably. The reliability of communication therefore has a direct impact on estimated capacity limits. To model this interaction, stochastic distributions of latency and packet loss have to be implemented within simulation simulations in a manner that both average and worst-case headway values become available and dependent on nominal parameters are no longer used. The other aspect of capacity evaluation is the station constraints. As the number of tracks is limited and the allocation of platforms is governed by rules, the output of a populated corridor is often not limited by the inter-station running, but rather by the bottlenecks on these nodes. These limitations are included in performance models, which limit the number of tokens in Petri net places that are used to model station tracks.

This enables the congestion to accumulate in the simulation frameworks as congestion accumulates at a critical point where arrival rates are higher than service rates (Daniel Knutsen, 2025). Passenger heavy routes with short interstation routes further modulate output, a small change in the average dwell time would lead to missed slots in departure sequences and decreased sustained line capacity even with theoretically permissive signalling. Macro-level modelling methods are able to model capacity based on optimization of the movement authorities on a comprehensive network layout in response to forecast demand. The results of such models are generally the production of viable train frequency ranges, but with safety levels of integrity incorporated into separation calculations. Conversion of these outputs to measurable system KPIs is done by refining these outputs, that is, by simulating them via macro or micro-level layers at which such details as individual braking curves, and their interaction with gradient profiles, are taken into account. Such a stratified strategy will make sure that the figures of headline capacity are not based on theoretical maxims which are not achievable in reality. The Hardware-in-the-Loop environment supplements this test by allowing actual signalling hardware, OBUs, RBC communication unit to directly engage in simulated traffic flows. In controlled laboratory experiments, operators can simulate congestion conditions or diminished communications modes to empirically characterize the speed of moving authority redistribution in restoring target headways following disruption. Such empirical data sets facilitate calibration of simulation models to be applied in broader forecasting activities. An indirect overlap between energy use and capacity measures may occur when the regenerative braking plans are part of the operations schedules.

The adaptive speed control that seeks to maximize the regenerative potential may occasionally require a slight change in the headway targets either to have a slightly longer separation in slowing down stages or to coordinate acceleration profiles between trains traversing a change in gradient. In the case where energy saving goals are equally important to output goals, composite KPIs can weighted score the train frequency per hour and net energy saving percentage relative to base timetables. Qualities of dependability should also be incorporated in the capacity measurement processes since regular system failures or partial mode failures will lower efficient output in the long run. Probabilistic adjustments to the raw capacity values are based on availability metrics based on data on failure rates. Thus, any calculated maximum flow could be scaled by an availability factor of 0.98 of a signalling subsystem and reported as an operational KPI. Scenario variability is of significance to decision-makers when relying on such metrics, by testing the same infrastructure with different signalling logics (e.g. fixed vs Moving block) (Daniel Knutsen, 2025), one can not only test the differences but also the resilience properties to perturbations in the system, such as unscheduled stops near high-density stations. Booleans modelling of stop indicators triggered by over MRSP threshold assists in determining the dynamism to signalling rules in response to traffic disruptions around natural bottlenecks. Finally, to build valid capacity-related metrics, there is need to balance macro policy goals with microscopic detail faithfulness. One the one hand is the strategic objective, the trains per hour that can be delivered safely within integrity limits, and on the other is a complex network of technical constraints, physical blocks/computed envelopes, deterministic update constraints, communication delay constraints, homogeneous rolling stock capacity/heterogeneous fleet performance profiles. The combination of these factors generates the indicators that are strong enough in planning but sensitive enough to determine constant changes in operation.

3.1.2 Motion Regularity

Motion regularity is the capacity of a railway network to ensure a stable, predictable and steady movement of trains on a line. In contrast to safety, which tries to avoid collisions, or line capacity, which tries to assess the number of trains a line can hold, motion regularity tries to assess train operation quality and continuity.

Laid down in practice, motion regularity is the adherence to the planned speed profile by a train without unnecessary braking, impulsive acceleration, or long stops due to signalling or traffic upsets. A very regular movement is one where the speed changes slowly, the stop and go movements are few and far between and there is little deviation to the scheduled schedule.

In the simulation setting that is created in this thesis, the regularity of motion is directly affected by the signalling logic. A Fixed block (FXB) system is a system in which trains respond to discrete block states. Upon entering a yellow or red signal, a train is required to enter into a prescribed braking curve, which can result in slow deceleration and even full stops although the line ahead of it may be free soon after (Barbaro, 2021). This discretization in blocks may produce oscillatory speed pattern and low smoothness, particularly during heavy traffic.

Conversely, Moving block (MVB) system obtains movement authority by considering the actual distance between the successive trains. As the safety distance varies with the real speed of the rear train as opposed to set block lengths, the braking limitations are more adaptive. Such dynamic spacing minimizes the unneeded decelerations and enhances the flow of motion especially when the traffic remains variable. Regularity of motion is hence a significant measure of the quality of operation. Irregular motion leads to higher rolling stock mechanical stress, increased consumption of energy owing to repetitive acceleration cycles, reduced passenger comfort, increased sensitivity to road noise.

Through quantitative analysis of regularity in motion under varying operating situations, the simulator points to the effect that signalling philosophy has on the overall system behavior of the railway. The findings prove that both FXB and MVB are not conclusively superior, their performance varies according to the amount of traffic in the road, service patterns, and disturbance conditions.

Here motion regularity can be regarded as a complementary view to safety and capacity, which gives an understanding of the efficiency and smooth flow of trains concerning the limitations of the signalling system.

3.1.3 Commercial Velocity

Commercial velocity is one of the most significant operation indicators of a railroad, because it directly indicates the successful service delivery that both operators and customers experience. It is determined by the distance covered along a railway line over the total journey time taken to get the service and acceleration, braking, station dwell time and delay due to interaction with traffic or because of signalling.

Commercial velocity, unlike instantaneous speed or maximum permitted speed, reflects the cumulative effect of infrastructure attributes, business plans, and traffic policies and management. It thus gives a real picture of system efficiency as opposed to the capability of the vehicle.

Within the context of this thesis, the concept of commercial velocity is not addressed as a distinct key performance indicator but rather appears as a synthetic effect of the analyzed KPIs, i.e. line capacity, regularity of motions, and energy consumption. All these indicators affect the overall travel time and consequently, affect the resultant commercial speed (Daniel Knutsen, 2025).

In the view of motion regularity, the regularity of commercial velocity is highly dependent on the smoothness of the movement of trains. Irregular movement which is marked by repeated braking, speed variation, and stop-and-go implementation boosts travel time despite the unchanged maximum line speed. In Fixed block signalling systems, trains are controlled by discrete movement authorities which is calculated on predefined block lengths set to worst-case braking scenarios. The conservative mode has the potential to cause a premature deceleration as the train follows a restrictive signal even in the case where the previous train has cleared the section immediately before it. The subsequent unwarranted braking and the consequent re-acceleration stages lower the effective average speed along the route.

In contrast, Moving block signalling systems assign movement authority in real-time, depending on the actual distance per train and the real-time braking capacity of the trains in front of the one being controlled. Since the safety distance is conditioned by the current working conditions and not a Fixed block division, the reduction of speed is more adaptive. This lowers the incidence of conservative braking stages and improves the traffic flow. Due to this, the total travel time can also reduce, which results in the increase of commercial velocity (Daniel Knutsen, 2025).

The capacity of lines also is decisive in the setting of commercial velocity. A signalling system that increases capacity by decreasing the headways allows an overcapacity of trains to run on the same track. But when spacing strategies are too conservative the trains can take additional time to await movement authority extensions particularly during heavy traffic. This communication among trains enhances the variability of the travel time and reduces the commercial speed of trains. Thus, the optimization of the capacity should be reconciled with the necessity of stable and constant movement.

The commercial velocity is also indirectly related to energy consumption. Repeated braking and accelerating moves raise energy demand and usually relate to less frequent movement. A signalling system, which encourages smoother paths not only uses less energy, but also helps to cut down on the total amount of time that is spent in travelling. In this regard, the increase in the regularity of motion also leads to the increase in the energy efficiency and the commercial performance.

It should be emphasized that commercial velocity does not directly determine safety. Both Moving block and Fixed block systems are developed to ensure safe distance between trains. In its place, commercial velocity measures the effectiveness of managing that safety constraint by the signalling philosophy. It hence reflects the cost of operation of safe separation in various technological methods.

In the context of the comparative analysis approach as will be employed in the current thesis, commercial velocity may be understood as a global outcome variable, which is a synthesis of the joint impacts of signalling logic, traffic density, infrastructure characteristics, and train performance. The differences in motion regularity and capacity between Fixed block system and Moving block system inherently come in as differences in overall travel time and, by implication, in commercial speed.

That is why, despite the fact that commercial velocity is not one of the main KPIs, it is a useful integrative measure. It provides a balance between technical analysis of signalling strategies, and the real goals of the railway operation, i.e. to decrease travelling time, increase the reliability of service, and also get maximum use of infrastructure without compromising on the critical safety standards.

3.2 Measurement methodologies

3.2.1 Analytical modelling approaches

The modelling methodologies of railway signalling performance appraisal aim to bring the links between operational variables, physical constraints, and safety requirements to the constructs that can be computed and compared to aid predictive and comparative analysis. These approaches will convert qualitative concepts, like safe separation or efficient output, into mathematical forms whose parameters may be varied systematically. Based on the capacity, safety, and efficiency dimensions illustrated in previous Section 3.1.1, this kind of modelling enables theoretical maxima and minima to be ascertained under certain assumptions in addition to sensitivity to the change of technical or environmental conditions. The derivation of headway formulas of various signalling architectures is one of the underlying ideas. In Fixed block modes the headway H can be frequently represented as a function of constant block length Lb, maximum allowed speed v"max" and dwell time elements:

$$H = \frac{L_b}{v_{\text{max}}} + t_{\text{dwell}} + t_{\text{clear}}$$

The t"clear" here is used to represent any window that is required to allow the detection systems such as track circuits to determine that no movement is in the way before new movement authority is issued. This deterministic type has a direct relationship between infrastructure-defined segmentation to the realizable line capacity. It implicitly supposes homogeneity in the rolling stock braking capacities. The sensitivity analysis of Fixed block headway can be used to see the effect of decreasing Lb or increasing block clearance verification and keeping all other parameters constant on output. Analytical formulations in Moving block situations change to dynamic spacing envelopes, the size of which is based on instantaneous train state variables (velocity v, deceleration ability, communication delay tc). An abridged safe distance requirement would look like:

$$D_{\text{safe}}(t) = \frac{v(t)^2}{2\,a_d} + v(t)\,\tau_c + M$$

Where M is a margin that represents the uncertainty in localisation and reaction times. The change of tc within a reasonable range, e.g., raising it to 5 s in simulations, after 1 s, shows how the elements of communication play a crucial role in the reachable headways by increasing and decreasing D safe. Simulation platforms evaluate analytical models optimized on these parameters against stochastic disturbance inputs to obtain baseline curves. There are some cases of hybrid operation that require equations that mix terms of both fixed and Moving block that form functions of pieces where dynamic margins are used in Moving block regions and then return to Lb specifications of a stationary body at the limits. Here we have the emergence of boundary alignment variables as nontrivial transitional constants as transitions might need positional revalidation by trackside detection systems prior to a train obeying the new regime in all its separation rules. These constants enter into general network throughput equations which exhibit efficiency dips at regime interfaces. In addition to headway estimation, analytical modelling can solve the problem of compliance with braking curves by using parametrical expressions based on ETCS standards. Braking curves can be represented as polynomials or piecewise-linear curves by a representation of the stepped enforcement zones, service brake then emergency brake range using MRSP values and gradient data. With gradient introduced by modifying the deceleration items, one obtains:

$$a_{\text{eff}} = a_d - g\sin(\theta)$$

Where g is the acceleration due to gravity and th is the track slope angle. The approach of applying gradient adjusted deceleration within the technology of stopping distance application involves topology impacts on the surroundings directly into safety margin computations. Th variable analysis can be used to measure the change in both the capacity potential and the safety reserve simultaneously between uphill and downhill conditions. The other use is in energy-consumption modelling with signalling induced profiles of control. A net energy model may add traction energy demand by segment and offset regeneration returns during braking events:

$$E_{\text{net}} = \sum_i \left(E_{\text{traction},i} - E_{\text{regen},i}\right)$$

Signalling logic affects such terms by determining the periods of acceleration and placing decelerations on transition of movements authority. Comparative analytical simulation of the FXB and MVB cases by running the same gradient maps can reveal circumstances when regenerative braking recovers more energy than extra acceleration dissipates. These types of models come in especially handy when the efficiency KPIs are to be balanced with the throughput needs. Aspects of dependence are combined with the formulations of analysis where the probability distributions of subsystem failures are introduced in the calculation. As a case in point, any deterministic capacity function is altered by the introduction of an availability factor As of critical subsystems:

$$C_{\text{effective}} = C_{\text{theoretical}} \cdot A_s$$

Assuming As=0.98, then even the best signalling configurations are found to lose measurable throughput just because there is a down time expectation. An extension of this method uses failure mode categories of varying mitigation effects such as loss of communication channel versus malfunction of localisation sensor and assigns probability of their occurrence. These local analytical constructs are often incorporated in macro-scale optimisation models in complex network-wide analyses on the model of the constraints of signalling rules. Linear programming or mixed-integer models are used in dealing with the allocation of timetable slots where the objective terms are to optimize the number of trains dispatched per unit time plus penalties in case of violation of the safety margins based on terms such as Moving block safe distance.

When the stochastic parameters are cause-and-effect and the dynamic envelope is to be varied in a nonlinear manner, more realism is gained at the expense of tractability. Simplifying approximations based on analytical derivations become useful here to constrain solution spaces before they are refined by simulation. When the theoretical results of equations like Fixed block headway, Moving block safe distance, or net energy consumption have been incorporated into Hardware-in-the-Loop test systems to be verified, it provides target ranges that must be approximated by live hardware experiments of realistic protocol interactions between RBC software modules implemented in Eclipse and onboard control logic implemented in MATLAB-Simulink® blocks.

The fact that the predicted and observed value differ points out differences that are due to either oversimplified assumptions (e.g. assuming packet jitter does not vary) or systemic latencies that cannot be modelled in a model but are observable in real systems. These analysis methods have values besides being able to directly quantify it, but also in sensitivity diagnosis, determining which input parameters have the greatest effect on output measures, therefore directing refinement priorities during simulating and hardware prototyping stages.

The maintenance of their standardised formulations as per the dictates of interoperability guidelines such as ETCS SUBSET-026 makes their results have transnational applicability without having to undertake massive recalibration exercises where underlying infrastructure has comparable normative underpinnings. Nonetheless practitioners know that pure analytical solutions will always abstraction away some nonlinearity of operation of the railways; the best use of them is to set bounds on expectations early in design before resources are expended on computationally more demanding stochastic or micro-simulation models with full spectrum operational variability.

3.2.2 Simulation-based approaches

The use of simulation-based methods takes a central position in the process of evaluating the performance of railway signalling by virtue of the fact that it is the only method that allows the complex interaction of infrastructure, rolling stock, driver behavior and control logic to be studied under diverse operational conditions at a lower cost and without engaging the risk involved in conducting real-world experiments. Analytical models provide limited accuracy and simplification, whereas simulations extend their models into dynamic conditions with temporal dynamics, stochasticity and nonlinear interdependences that more faithfully model the behavior of a real network (Herrero, 2024). Simulated settings are also flexible, and many scenarios can be iterated in which the parameters of gradient profiles, the reliability of communication or changes in dwell time can be systematically perturbed and the other features kept constant. Practically, such strategies are usually applied at several layers of abstraction that are stacked on top of a single architecture. At still higher levels, macroscopic features such as throughput potential of various signalling strategies under an assumed demand profile are seen using coarse-grained network or corridor models.

These representations can import the headway relationships which are determined analytically and are enhanced with the scheduling constraints and the junction priorities and the distribution of the dwells at the station which are obtained using historic data. These macro layers frequently work in discrete-event mode, with trains being modelled as tokens moving over segments and events being modeled as a change in signal state or block occupancy. Under this paradigm, Fixed block models track block entry and clearance events through feedbacks on track circuits, but dynamic movement authorities are computed by dynamic positional updates and rolling stock braking capacity by Moving block configurations. Simulations at the mesoscopic scale, at the seconds scale instead of minutes, solve train runs to analyze transient capacity loss and recovery effects after disruptions. This time scale is necessary to research the effect of various architectures on adversities like delayed clearances into congested stations or reduced acceleration because of adhesion loss on inclines. A more accurate description of the interaction of the terrain with control decisions is provided by the incorporation of gradient-dependent tractive effort curves based on data.

This level of state variable usually contains speed profiles on each link, instantaneous separation distance between each train pair and scheduled and actual arrival times at control points. The most elaborate one is a combination of continuous vehicle dynamics with discrete signalling logic, a structure especially appropriate in a system such as MATLAB-Simulink®, where train side subsystems (braking controllers, odometry modules) may be executing alongside trackside logic (interlockings, RBC algorithms). In this case characteristic forces may be incorporated, tractive motor force given by a regime of speed control, resistive forces due to aerodynamic drag and contact conditions on the wheels to the rail, as can be found in previous dynamical work. These are fed into longitudinal equations of motion that generate accelerating history that subsequently feed into the development of safety envelope under Moving blocks operation. Explicitly injected communication latencies are sampling delays or jitter functions into the rate at which position reports of OBU were communicated to RBC.

The variable series of latency were taken as part of the experimentally determined wireless links. The use of simulation-controlled experimentation in purely virtual models is not limited to Hardware-in-the-Loop setups. Indicatively, an OBU prototype running its onboard software stack can be connected to a simulated RBC implemented in Eclipse using real communication protocols like UDP. The simulator generates artificial trains positions streams that are fed through the physical OBU and braking or acceleration commands are sent into the virtual environment. This two-way circuit allows real-time evaluation of timing tolerances and fail-safe reactions in the presence of controlled fault injections, e.g. intentional bursts of radio packets, and investigates degraded mode transitions in the absence of live rail risk. Moreover, distributed simulation systems may be used to allocate trackside systems and train side elements to different computational units linked via a lab network; it is a more true-to-life simulation of the latencies caused by geographically distributed systems.

The aspect of scenario composition is fundamental in obtaining useful performance measures within simulation-based approaches. Representative cases run through nominal flows that are equivalent to timetable plans up to disturbed ones where inversion of sequences may occur owing to missed links or emergency halts invoked in the middle of the section. The hybrid operational zones, in which fixed and Moving block regimes are used in the same line, are of particular interest as these zones demonstrate transitional penalties or compatibility conflicts which cannot be observed when only the isolated regimes are considered. These simulations model regime-change events as discrete events: as they enter the static blocks positional revalidation can introduce measurable entry delays whose cumulative effect is the daily throughput counts despite their shortness at any given transition. Dependences between energy consumption patterns and signalling rules are also made explicit in high-resolution simulations in which regenerative braking logic is turned on. Advanced driving assistance systems have profile smoothing algorithms that modify throttle modulations and brake modulations according to different gradients: their interplay with movement authority sequencing defines net regenerative yield versus standard timetables.

Herein a comparative scenario analysis may indicate that at some set slopes MVB control sequences can permit the commencement of braking phases at earlier instants with substantially better energy recapture efficiency than FXB sequences limited by the full-block clearance timings. Nevertheless, these results are extremely sensitive to consistency of RBC-OBU updates in the face of varying network loads, a variable that is easily parameterized in simulation inputs to explore sensitivity. Dependability analysis when stochastic failure insertion is done is another area that is reinforced through simulation environments. Hazard-based fault tree structures may inform the selection of which behavior of components is algorithmically impaired during execution; in hybrid simulators, Petri Net representation counts incidences of protective state transitions that happen after a hazard is detected, but before the hazard thresholds are reached. A repeat of the same disturbance patterns in other signalling architectures of the same simulator framework can be assured of comparative statistics on safety availability, fraction of time all the protection functions have been active, as due to systemic differences and not exogenous variation in the scenario. Any interface of simulation layers requires a meticulous calibration to ensure that macro-level patterns of performance can be consistent with micro-level physics-based constraints. Parameters that are transmitted between levels include MA validity time durations that are found in detail at the upstream and consumed as constants at the downstream, misalignment here can cause impractical elasticity in compression compression of train spacing at higher scales. The use of calibrated multi-scale constructs can thus maintain coherence in the cascading of policy-oriented optimizations to implementation-sensitive design choices which are tested at fine resolution in either HIL rigs or pure software models. With these combined strategies simulation-based methods transcend demonstration aids, they evolve into scientific aids that transform theoretical laws and protocol dictates into quantifiable and reproducible insights in capacity, motion regularity, efficiency realms all of which are plotted together in a variety of infrastructure configurations. Because execution cost remains bounded compared to extended field trials while faithfully embedding standardized requirements like those in ETCS SUBSET-026, such methodologies form a logical anchor point for continued system evaluation throughout both developmental iteration and gradual operational rollout phases across mixed-technology railway networks.

3.3 Building simulation Environment

3.3.1 Various Blocks and their purpose

Leading Train subsystem is a subsystem of the active development of the first train that will run along the railway line. Its main purpose is to model the physical behaviour of a railway vehicle during traction, coasting and braking with consideration of Maximum Recommended Speed Profile (MRSP). The subsystem incorporates longitudinal dynamics, traction / braking effort curves, resistive forces and speed supervision logic to calculate real time outputs like position, velocity, and acceleration.

Consistent with the modelling philosophy used in performance comparison studies of performance of fixed and Moving block signalling systems, Leading Train is the reference vehicle whose state directly determines the movement authority of the following train. The most important inputs to evaluate the safety in the signalling logic are its position and speed. The subsystem can thus be described as a vehicle dynamics modular as well as a dynamic constraint generator to the supervisory control layer. The products of the Leading Train consist of organized train state signals (TS), speed threshold data to be displayed, and internal dynamic states necessary to compute inter-train headway. These products guarantee tight-loop communication between signalling control and vehicle motion.

Trailing Train subsystem represents the actions of the subsequent train which are governed by the signalling system. The Trailing Train has a Movement Authority (MA), unlike the Leading Train, the movement of which is not limited by the movement of preceding traffic (Movement Authority, 2003). The subsystem gets MA as input in the Radio Block Centre (RBC) and converts them into a moving speed reference profile. This reference is then introduced by longitudinal vehicle dynamics the same in structure as those of the Leading Train. The framework ensures that performance differences are caused only by signal constraints but not modelling bias by assuming the same physical modelling assumptions on both trains. The Trailing Train is constantly measuring its distance against the MA limit and braking curves where needed. This process is the same as in signalling system performance literature where the subsequent train changes its motion based on safety envelopes based on the position of the lead vehicle. Furthermore, the subsystem produces the results of visualization (speed limits and train positions), which gives the opportunity to immediately compare theoretical speed limits and the real operation speeds.

Radio Block Centre is the intelligence centre of the system in terms of signalling. Its aim is to receive real-time information of the both trains and compute a safe Movement Authority of the Trailing Train. The RBC reflects conceptually the logic of Fixed block (FB) or Moving block (MB) signalling according to the choice of configuration. Under the Fixed block paradigm, movement authority is identified according to set occupancy conditions of blocks. Conversely, in the Moving block strategy the authority limit is determined dynamically with the actual location of the Leading Train and braking performance assumptions. The RBC is led to receive TTS (Trailing Train State), LTS (Leading Train State) and Headway information. By means of these inputs, it estimates the conditions of separation and decides on the acceptable distance of movement. This is a direct reflection of the supervisory principles that were addressed in the comparative signalling literature, where the centralized control calculates limits to movement in terms of train detection and braking safety margins. The Movement Authority (MA) is the RBC output and sent to the Trailing Train to be enforced.

The headway block determines the current spatial difference between the Leading and the Trailing trains. This measure is essential to safety validation and system performance measurement. In Moving block systems, the headway is a continuous variable, and not a discrete constraint of blocks. Thus, it is necessary to have real-time computation of train separation. The headway signal is directly recirculated into the RBC where it assists in computing MA and enables performance measurements including minimum separation distance and capacity utilization to be determined. This block is a good bridge between vehicle motion and signalling supervision that is physical.

The signal of the Movement Authority is conditioned and sent out between the RBC and the Trailing Train. This interface makes sure the MA is built in such a way that it can be integrated with the logic of the speed supervision of the train. The MA determines the farthest point to which the Trailing Train can be allowed to move.

Braking curves are implemented when the train approaches this limit in order to enforce conformity. This Moving block signalling strategy is a recreation of the safety enforcement approach of the fixed and Moving block signalling philosophy.

The entire architecture creates a closed-loop supervisory railway architecture. As a result of its movement, the Leading Train creates dynamic constraints. These constraints are processed at the RBC and Movement Authority is calculated. The Trailing Train readjusts its dynamics. The new states are fed to the RBC and so the loop is complete.

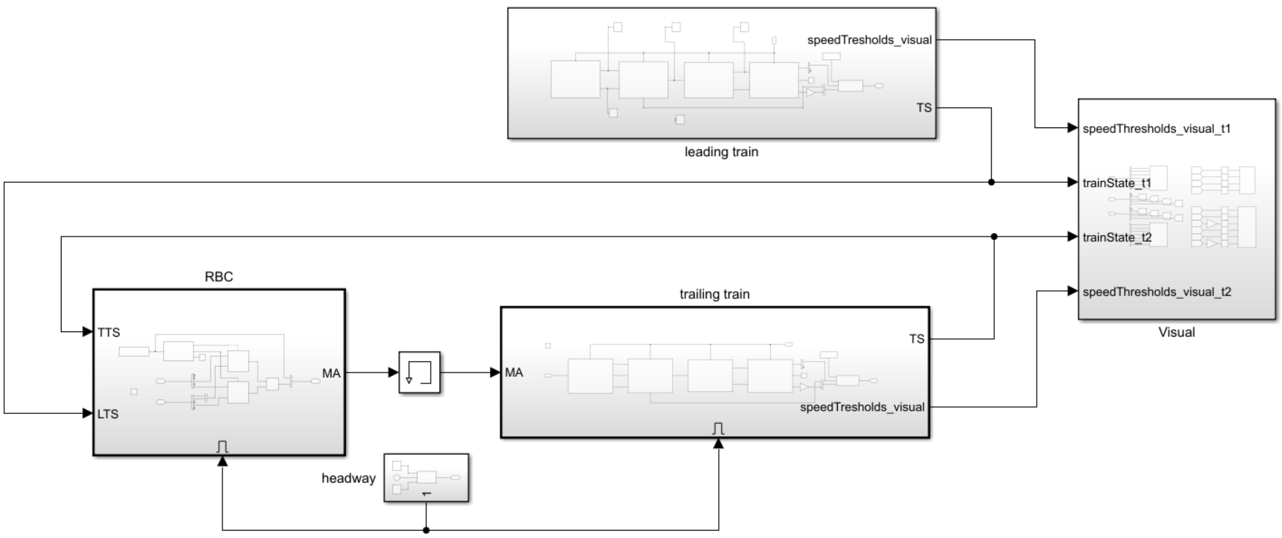


Figure 3.1: Overall architecture of our simulation environment.

3.3.2 Leading Train Characteristics

Leading Train subsystem depicts the entire dynamic and supervisory model of the reference train that is running along the railway line. The main role of it is to make realistic train movement based on infrastructure constraints and produce state variables needed by the signalling system. The subsystem is structurally organized to combine the speed profile generation, supervisory control logic, longitudinal vehicle dynamics and state computation in a closed-loop architecture. Such a modular framework is important to guarantee that infrastructure constraints, operational behaviour and physical movement are all integrated logically in one simulation context.

The MRSP generation block is the starting point and it specifies the Maximum Recommended Speed Profile alongside the track. This block sets the permissible speed based on position by taking into account infrastructure-related constraints including line speed limit, station zones, and operational restrictions set. Along with the MRSP signal, the block generates a station proximity signal which determines when the train is approaching a station area or is actually in operation. These outputs constitute a limit to the allowable velocity of the train and serve as reference limits to the following speed control rationale. The model allows the separation of infrastructure based speed limits and signalling logic to ensure that nominal operational constraints are always imposed.

The MRSP and the measured train speed are sent to the speed control block that produces the traction or braking command necessary to ensure that the admissible profile is followed. This block is the supervisory behaviour of onboard speed protection systems. It determines the difference between the actual and allowable speed limits and the traction effort, coasting, service braking or emergency braking to be applied. The controller will therefore make sure that the train does not move beyond the safety margins and yet still maintains realistic operating behaviour. A force command is the output of this block and it has a direct effect on the physical motion of the train.

The longitudinal dynamics block converts the ordered commanded traction or braking force into real movement through a simplified version of Newtonian mechanics. It calculates the net longitudinal force on the train by summing the traction or braking forces with pulls on the train with the resistive forces of rolling resistance, aerodynamic drag and gradient pull. Acceleration is calculated based on the net force, and the vehicle mass; this is then integrated to get the velocity and position. This step performs the check to make sure that the simulated motion is physically consistent and limited by realistic traction and braking capabilities. The architecture ensures clarity by decoupling control logic and physical modelling and enables the future optimization of the vehicle dynamics without having to modify the supervisory logic.

The last block of subsystem is the state computation block. This block consolidates the variables which are computed dynamically and transformed into structured outputs needed by the rest of the system. It transmits the new train position, speed and block occupancy data to form the Train State (TS) signal which is sent to upper-level systems like the Radio Block Centre. It also prepares signals to be displayed and monitored. At this step, the Leading Train subsystem turns out to be an integrated source of both supervisory feedback and physical state information.

The general Leading Train subsystem layout is sequential and stratified with the infrastructure restrictions determining admissible speed, supervisory logic imposes adherence, longitudinal dynamics produce realistic movement and state computation structures the results so the system may interact with other systems. This design will allow the simulated train to act in accordance with the railway operational principles as well as be compatible with signalling supervision and real-time implementation goals.

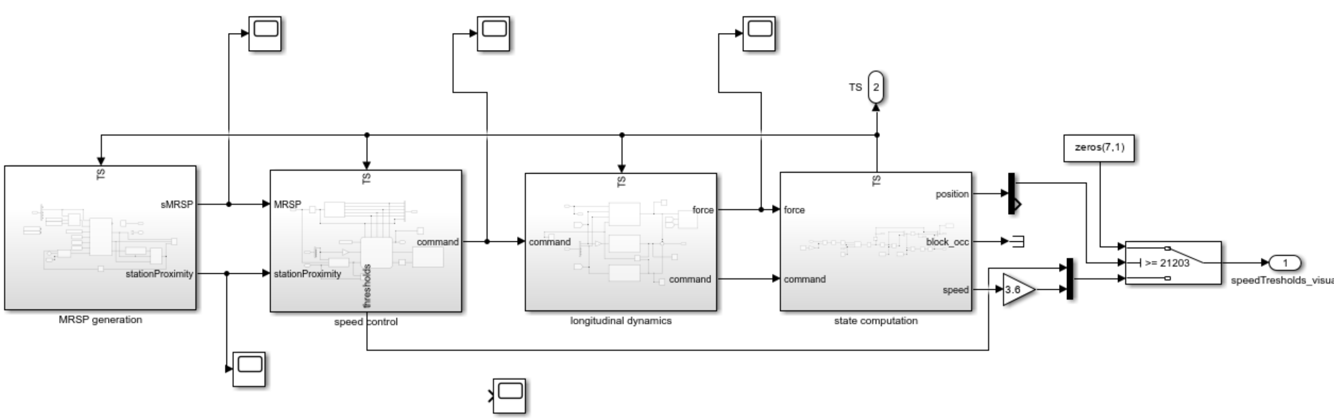


Figure 3.2: Leading train simulation blocks.

3.3.3 Trailing Train Characteristics

Trailing Train subsystem is similar to the physical and supervisory architecture of the Leading Train except that its behaviour is also affected by signalling constraints received through the Radio Block Centre (RBC). The train at the head of the train is permitted to run at the limits that are specified by the infrastructure; however, the train at the rear needs to dynamically adjust the allowable train speed in response to the movement authority (MA) and the separation restrictions created by the signalling logic. This subsystem is therefore very important in measuring the management of headway and safety performance in both Fixed block and Moving block regimes.

The subsystem starts with the MRSP generation block where both the movement authority (MA) and the static infrastructure profile are passed by the RBC. The trailing train has a dynamic MRSP, unlike the leading train whose MRSP is mostly infrastructure oriented, because it incorporates signalling restrictions which can also change with time based on the position of the leading train and block occupancy. It is a block that calculates the permissible reference speed (v ref) taking into account the effects of braking curves, recommended deceleration rates, end-of-authority limits, and the proximity to the station. When the trailing train reaches the edge of its movement authority, the dynamic MRSP gradually decreases the allowed speed to provide safe braking profile. This will ensure that the train is able to halt prior to the end of its authority or the lowest safety margin with the main train.

The dynamically calculated MRSP is fed to the speed control block which compares the results with the actual speed of a trailing train. It establishes the same supervisory logic as the leading train, but with more stringent conditions that are imposed by the influence of signalling. The controller produces the traction or braking signal depending on the difference between the current speed and allowable speed limits. When a warning curve is crossed, service braking is used, and when a more restrictive threshold is crossed, an emergency braking logic is activated. The block, in this manner, also guarantees absolute adherence to constraints on signalling, but represents realistic behaviour of drivers or automated control.

The longitudinal dynamics block converts the command of the supervisory command into physical movement, providing traction and braking forces to the train model. Acceleration resulting is then calculated that takes into consideration train mass, force of resistance, and track gradient after which velocity and position are then acquired by means of integration. This phase makes sure that the movement of the train behind is physically consistent and within the actual traction and braking ability. Notably, since the MRSP can be dynamically updated as per changes in movement authority, longitudinal response of a following train can display adaptive deceleration schemes especially when moved-block signalling occurs.

The state computation block is the block that summarizes the dynamic variables; position, speed and block occupancy and produces the Train State (TS) signal. This is relayed back to the RBC, and the supervisory loop is complete. Also, speed and threshold values are visualized and monitored in performance. The block occupancy detection can be included in the system to know whether a given Fixed block is occupied or the dynamic separation criteria have been met in the signalling setup depending on the chosen signalling setup.

In its entirety, Trailing Train subsystem is a controlled vehicle model that is affected by infrastructure and signalling limitations. Its architecture allows the translation of movement authority limits into physically feasible braking profiles so that the relative operational performance and safety margins of fixed-block and moving-block systems can be compared by the simulation. The trailing train model is the most important component of assessing the headway optimization and system performance by its closed-loop communication with the RBC and dynamic adjustment to the varying authority conditions.

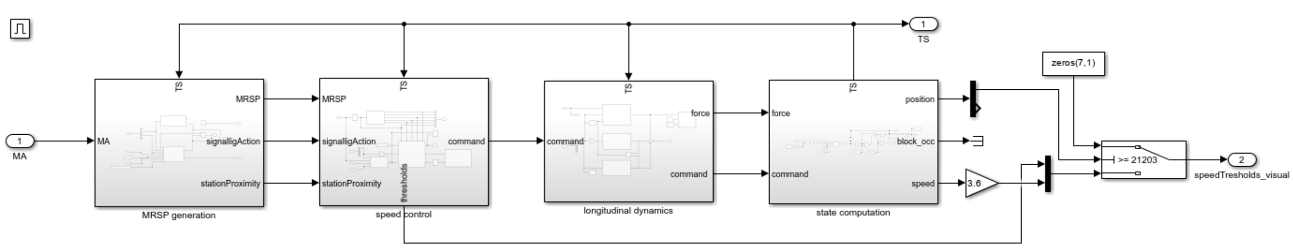


Figure 3.3: Trailing train simulation environment blocks.

3.3.4 Radio Block Centre

Radio Block Centre (RBC) subsystem forms the supervisory centre of the signalling architecture of the simulation environment. It is mainly used to calculate and transmit the Movement Authority (MA) to the following train using real time information it receives both through the Leading Train State (LTS) and Trailing Train State (TTS). The RBC complies with the current standards of railway signalling and provides a safe separation of trains at maximum efficiency. In the model, the RBC is given to be run within two different signalling paradigms; Fixed block (FB) and Moving block (MB), and it is then possible to make a systematic comparison between the two systems.

The signalling System input is a configuration switch, which controls the signalling logic that is operational during the simulation. The input of one trigger the moving-block logic whereas the input of zero triggers the Fixed block logic. This conditional selection is accomplished by the Signalling system selection subsystem that causes the LTS and TTS signals to be sent to the correct RBC logic block. The structure guarantees the co-existence of both signalling algorithm models with one another, but not at the same time due to their mutual exclusivity. This modularity allows one to be able to compare the performance under the same operating conditions.

The calculation of the movement authority in Moving block (RBC MB) model is calculated dynamically using the actual position and velocity of the first train. As opposed to using pre-determined sections of the tracks, the MA is determined by applying safe braking distance and minimum separation between the trailing train and the leading train. The RBC MB block constantly determines the spatial distance, relative velocity and the prescribed deceleration capability to identify the allowed movement limit. Consequently, the MA changes continuously with the movement of the trains, allowing smaller headways, higher line capacity, and safety constraints are maintained.

In Fixed block (RBC FB) setup the track is split into blocks of predetermined length. The movement authority is set by RBC FB block in accordance with the block occupancy data which is received using the state of a leading train. When there is a block in front of the trailing train which is occupied, the movement authority is limited to the former block of the safe end. This reasoning resembles the traditional signalling in which the separation between trains is achieved by not occupying the same stretch of block simultaneously. This technique has disadvantages compared to Moving block in that it introduces a conservative spacing, yet it is simpler structurally and deterministic.

Outputs at both RBC MB and RBC FB blocks are fed via a merge structure, so that it is only the active signalling logic that forms the final signal, MA. This Movement Authority output is then sent to the subsystem of the trailing train where it has a direct impact on dynamic MRSP generation and speed control logic. The system recreates the functioning of the major traffic management process of centralized control in the modern railway systems by a close-loop system in which LTS and TTS supply the RBC, and MA feeds the trailing train.

In general, the RBC subsystem summarizes the supervisory intelligence of the railway control system. The model offers a systematic and technically coherent system of assessing safety margins, headway reduction and capacity gains in the context of various signalling philosophies by combining fixed-block and moving-block algorithms with a flexible framework.

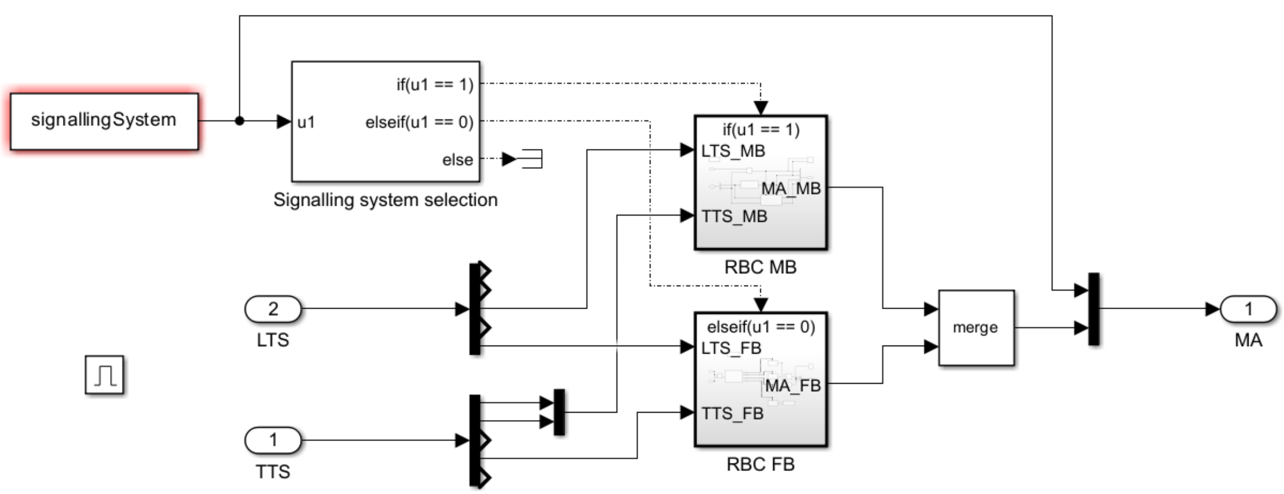


Figure 3.4: Radio block centre nomenclature containing activity blocks.

3.3.5 Output Visualizations

The output visualisation subsystem is in charge of converting internal simulation state to graphical displays, which can be understood by humans. It is not intended to affect the dynamics of a system but rather to offer a structured and consistent interpretation of the train behaviour, signal thresholds, traction-braking conditions, spatial development, and block occupancy. This division of computational logic and visualisation is what makes performance assessment clear and at the same time maintains the modularity of the simulation architecture.

The various supervision limits produced in the speed control layer are found in the speed thresholds visual inputs of the two trains (speedThresholdsvisualt1 and speedThresholdsvisualt2). These generally involve the Lower Curve (LC), Warning Curve (WC), Service Brake Intervention (SBI), Emergency Brake Intervention (EBI), the Movement Authority-derived MRSP and the actual train speed (Barbaro, 2021). These signals are split in the visualisation subsystem, and the corresponding blocks of speed displays (speedt1 and speedt2) are connected to them. The graphical response can be directly compared to the set thresholds and the actual operating speed and therefore it is possible to monitor compliance, overspeed and intervention activation. This hierarchy resembles actual railway control mechanisms, in which several speed envelopes are now tracked at the same time in comparison to the velocity of the train.

Each train has its trainState inputs which are broken down into the component traction and braking forces. Signals like positive traction force (pF), regenerative or resistive braking components (pR) and braking forces (bF and bR) are gleaned and diverted to specific displays. These signals are then sent to scaling or shaping blocks to normalize them to be represented graphically (Franc Mihalic, 2022). This gives the viewer a chance to examine the force balance at the acceleration, cruising, coasting and braking stages. The model helps to understand patterns of energy utilisation and control changes by visualising traction and braking contributions to gain insights into the control changes (crucially) when assessing the dynamic behaviour under both variable block and Moving block signalling conditions.

Position visualisation block is a combination of longitudinal position signals of both trains. Smoothing or shaping elements are used to pass these signals prior to displaying the signal, which makes the graphical representation continuous. The resulting plot can be used to directly observe the evolution of headway, relative spacing and convergence behaviour with time. Such a graphical representation is central in the area of signalling performance comparison and is used to evaluate the effect of various control strategies on train separation and capacity utilization.

The block occupancy visualisation section is notably relevant in a fixed-block signalling. In this case, position signals are converted to discrete block indices by scaling them by the reciprocal of the Fixed block length (1/FBL). These indices are then operated to establish occupancy states which are graphically illustrated. It allows one to have a straightforward graphic insight into which track blocks are used at a particular moment and how the occupancy changes travel along the line. With moving-block signalling, this representation will be less important to enforce safety but will still be useful in comparative analysis.

In general, the output visualisation subsystem is a diagnostic and analytics interface of the entire simulation. It maps the complicated internal variables- speed supervision threshold, traction and braking forces, spatial positions, and block occupancy conditions, into the graphical outputs that can be interpreted. This formalised visual feedback is crucial in the validation of model behaviour, the control interaction determination, and a quantitative comparison of the operational implications of fixed-block signalling systems and moving-block signalling systems.

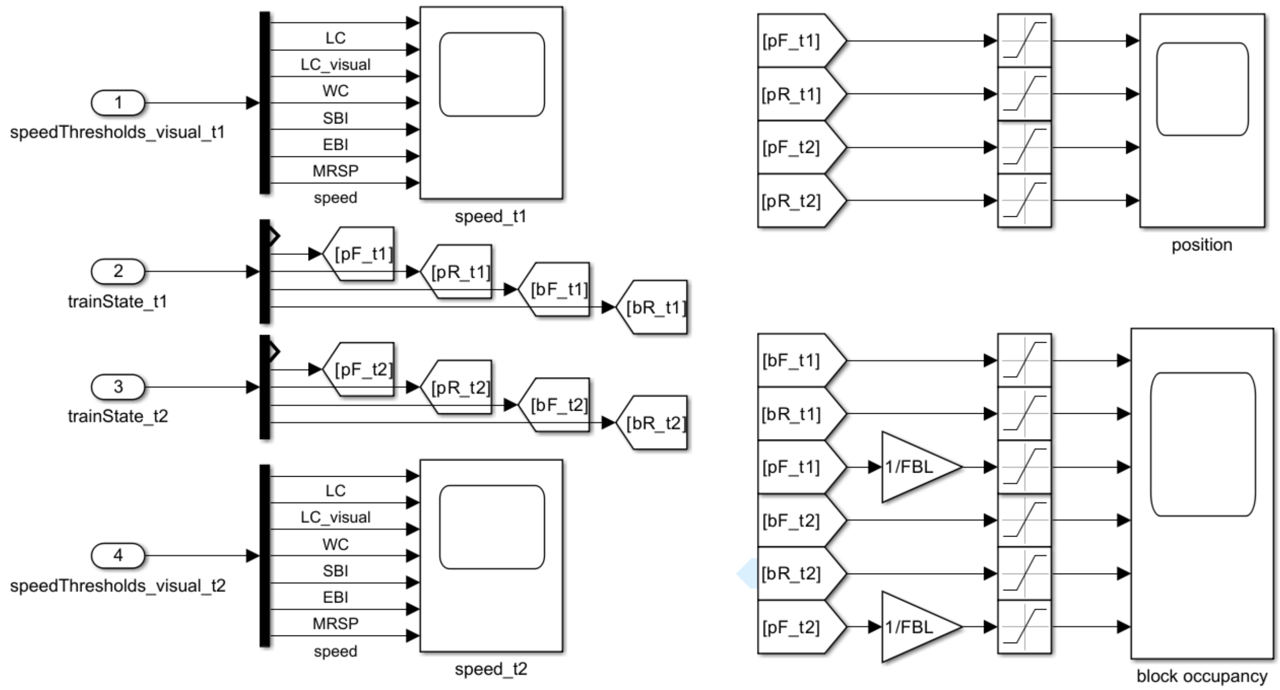
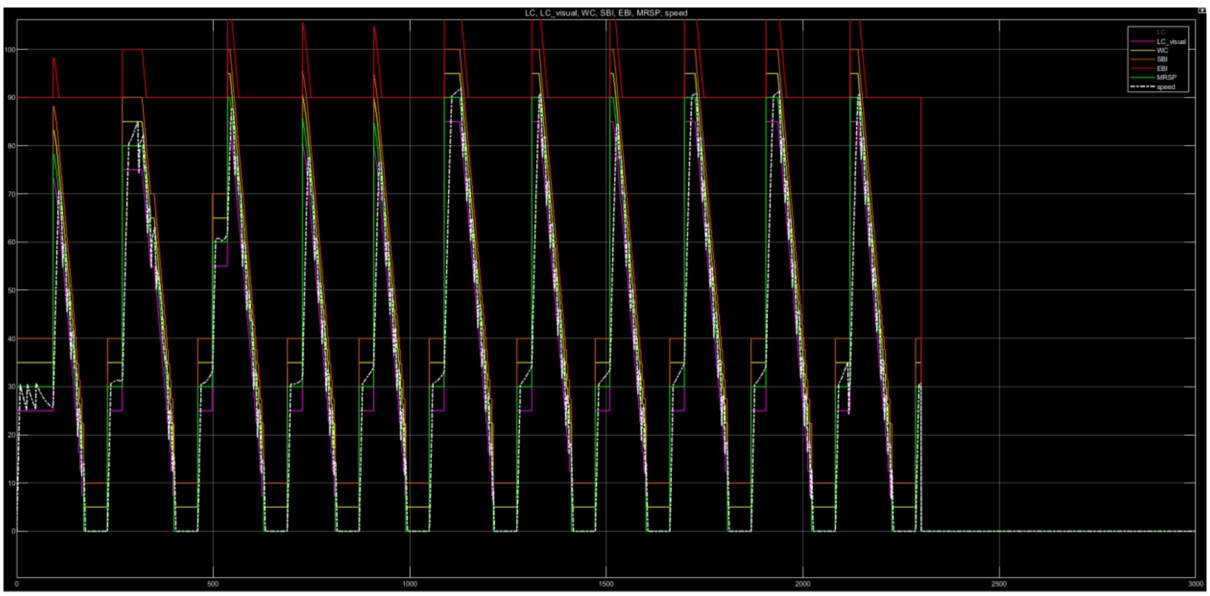


Figure 3.5: Various output blocks for visualising LT speed, TT speed, position and block occupancy.

4 Simulation results Parameters

4.1 Graphical Output

4.1.1 Leading Train Results Parameters



Graph 1: Parameters influencing Leading Train output.

The Maximum Recommended Speed Profile (MRSP) is the track speed limit which is set by infrastructure. In the case of the leading train, MRSP is the main upper limit of movement when the traffic is not constrained. The speed profile of the leading train is also largely constrained by MRSP and station stopping rather than movement authority constraints by other trains since the leading train does not have a proceeding train behind it. As a result, the dominant train usually utilizes MRSP more completely, and the envelope in which it functions is used as the reference point to assess the dynamic limits of train number two.

The Lower Curve (LC) is used to set the lowest limit of the nominal operating band of the driver model used by the leading train. It dictates the point at which traction is reverted after the braking periods. With the leading train, the primary effect on LC behaviour is due to station approaches and gradient effects, as opposed to the signalling restrictions due to occupancy ahead. Thus, the LC curve is very similar to the shape of MRSP with driver-specific offsets that correspond to the aggressiveness or the conservativeness of speed regulation. The extent of the smoothness of the acceleration phases between stations is directly determined by the interaction of LC with MRSP.

The LCvisual signal gives a plot of the LC threshold of the leading train. It mainly serves an interpretative but not functional role. The leading train scenario can be used to explain LCvisual, which would be used to demonstrate the margin between supervisory thresholds and nominal operating speed. As there is no other vehicle that impairs the leading train dynamically, the distance between LCvisual and MRSP indicates internal driver modelling behaviour and not external effects of traffic regulation.

The first supervisory threshold that is outside the nominal operating band is the Warning Curve (WC). In the case of the leading train, the WC is primarily determined by the next station constraints that are likely to be static constraints like the distance to the station or the permanent speed limit that is part of MRSP. Since the preceding train does not place any other restrictions, the WC activation of the leading train usually coincides with the foreseeable deceleration phases in front of the station stops. As such, WC behaviour of the leading train gives an idea of the responsiveness of the supervision logic under the conditions of infrastructural influence alone.

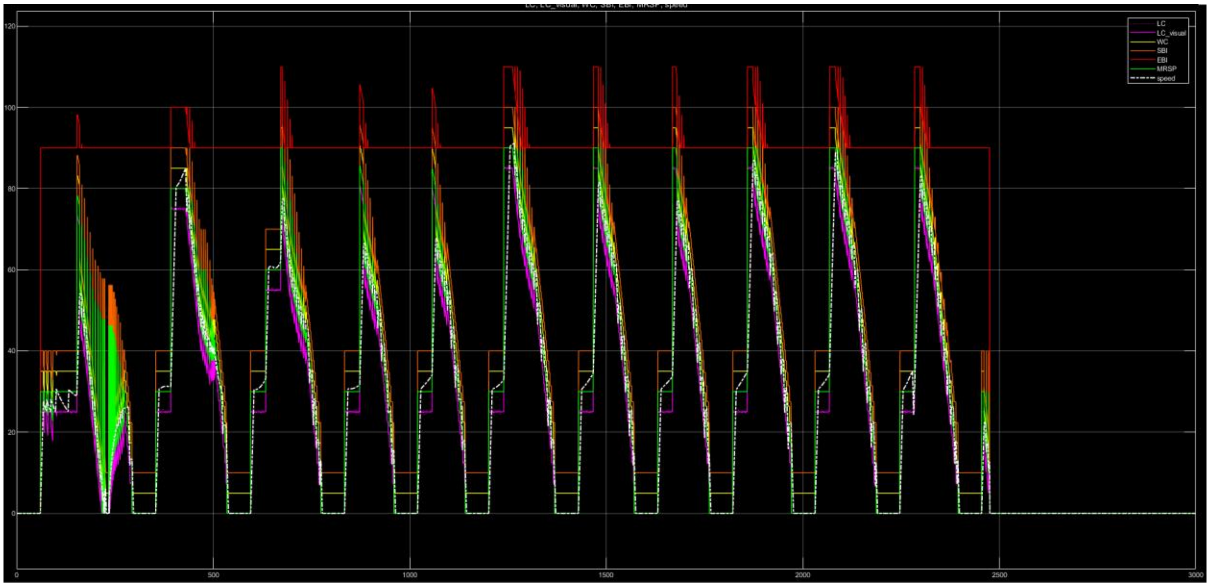
Service Brake Intervention (SBI) curve is an auto-braking line that is set to guarantee the adherence to MRSP and stopping targets. In the case of the first train, SBI is mostly activated as the train approaches a station, or at the entrance of lower MRSP. Its activation is an indicator of the computation of braking curves which depends on the capabilities of deceleration and the remaining distance by the system. Given that the dominating train is not affected by the preceding occupancy, SBI behaviour is the direct measure showing the interplay of braking performance and gradient effects, as well as recommended deceleration parameters.

The last safety boundary is the Emergency Brake Intervention (EBI) curve. In the case of the leading train, EBI serves as a protective measure concerning the over speeding in comparison to the speed limits set by the infrastructure. Under proper regulation, the real speed trajectory must be below EBI indicating adequate safety margins. Without traffic restrictions, the activation of EBI would normally indicate aggressive driving behaviour or the poor calculation of braking margin. Therefore, to the first train EBI is more of intrinsic safety enforcement than the risk reduction brought about by traffic.

The real speed signal is the dynamic response of the train that is in the lead to the traction signals, braking signals, MRSP limits and supervision thresholds. The speed profile of the leading train is mostly determined by the cycle of stopping at station and the geometry of the infrastructure since the leading train does not have dynamic movement authority constraints imposed by an approaching train. The speed curve pattern of acceleration-cruise-braking is the pattern of operation of the line, and the desired reference trajectory to which the trailing train has to adjust to both Fixed block and Moving block signalling. As a result, the behaviour of the leading train speed will dictate the development of the headway, distribution of block occupancy and the overall traffic stability in the simulated corridor.

Within the overall simulation framework, the leading train determines the baseline dynamics of the operational dynamics of the corridor. Its MRSP monitoring, braking policies and acceleration properties determine the time and space arrangement of traffic. In both Fixed block signalling and Moving block signalling, the constraints of the trailing train are eventually based on the instantaneous condition of the leading train. Hence, these supervisory curves of the leading train are crucial to the understanding of the behaviour of infrastructure-based limits spread through the signalling system, and define the capacity performance of downstream trains.

4.1.2 Trailing Train Results



Graph 2: Parameters influencing Trailing Train output.

In Moving block signalling MRSP still has the same operational role that it did with the static infrastructure-imposed speed ceiling, but now it has a different meaning. MRSP becomes not the limiting factor in cruise phases in MB operation. Rather it is an upper envelope on which the dynamically calculated movement authority runs. In the case of the following train, the actual safe braking distance calculations are often lower than MRSP, because of the real-time calculations of the safe braking distance relative to the train ahead. This leaves MRSP as a theoretical upper limit, and the practical speed limit as determined by the logic of dynamic separation.

Under Moving block conditions, the Lower Curve (LC) remains to establish the nominal lower maximum of the traction re-engagement, however, its form and frequency of activation is highly contingent upon the movement of the leading train. Since MB recalculates safe separation distance, any reduction in the velocity of the leading train is directly transmitted to the allowable velocity of the trailing train. Consequently, the LC oscillations can get more common or more compressed which shows dynamic adjustments, instead of just infrastructure-driven cycles. The LC then remains an indicator of the efficiency of the train to regain speed following the occasional dynamic constraints.

The Moving block signalling LCvisual signal is a visual representation of the movement of the operating band as a result of changing dynamic authority. Moving block, as opposed to Fixed block, involves continuous recalculation of supervisory thresholds, whereas in Fixed block, this is a discrete calculation at block boundaries. Therefore, LCvisual can demonstrate the smoother transitions and adaptive reshaping based on the speed and distance between trains relative to each other. It represents the limitation of driver behaviour not by sections but by a constantly renewed safety braking range.

In Moving block signalling, the Warning Curve (WC) is closely aligned to the real-time braking curve of the state of the leading train. As the top train slows down or when the top train is about to reach a station, WC automatically shifts downwards to the rear train. This repositioning is one of the fundamental strengths of MB systems: the speed monitoring in no longer discretized by block boundaries but recalculated based on the real-time train-to-train spacing. WC is therefore an early measure of separation speed adaptation as opposed to constraints based on infrastructure.

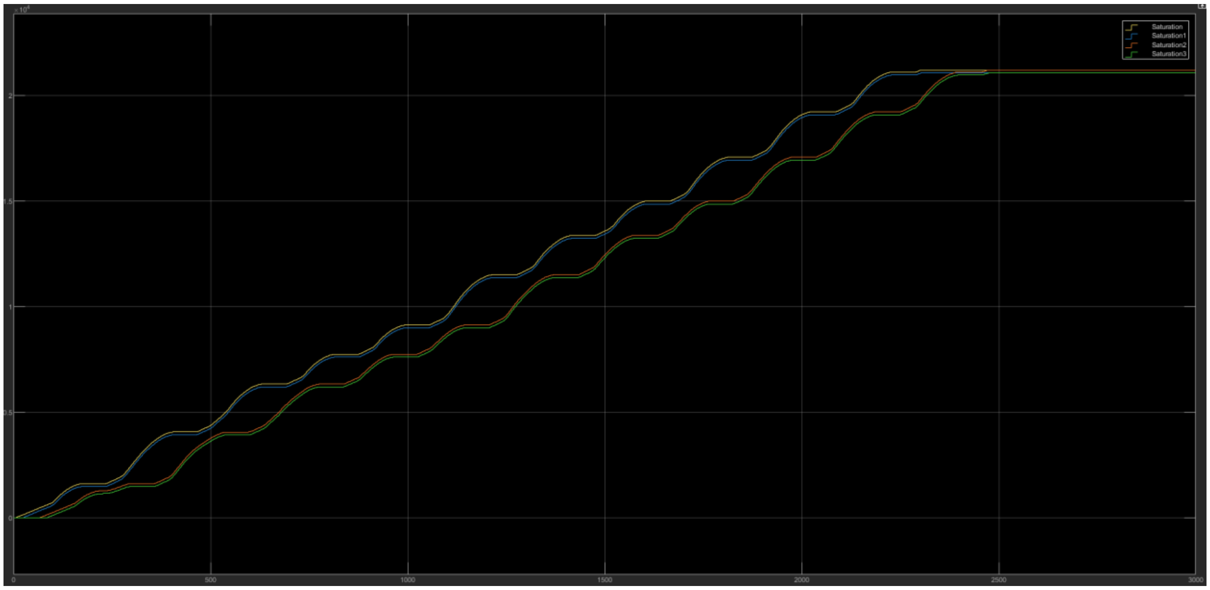
The Service Brake Intervention (SBI) curve under the Moving block operation indicates the calculated braking path that will ensure the leading train is not within a dangerous zone (Vahid Ranjbar, 2022). Its activation threshold is also constantly adjusted depending on relative speed and distance. SBI under MB normally supports more high cruise speeds with sufficient distance, but demands earlier deceleration with reduced spacing than Fixed block signalling. The line usage is enhanced by this adaptive behaviour without compromising the safety margins. The main concept of the Moving block is thus the essence of SBI; the calculation of braking authority is done as a dynamic relative motion instead of block occupancy.

Moving block systems have the Emergency Brake Intervention (EBI) as the final safety threshold based on worst case braking assumptions. Since MB is based on continuous separation monitoring, EBI curves can dynamically change their positions due to accelerated changes in deceleration of the leading train. Preferably, the actual speed must not exceed EBI. The sensitivity of EBI in MB points out the strength of the real time communication and computation at the Radio Block Centre (RBC), which could avoid collisions even in the abrupt leading train braking.

The reality of the speed profile of Moving block signalling exhibits a better response to changes in traffic conditions than Fixed block systems. MB allows progressive deceleration as opposed to sudden speed changes due to block transitions that are calculated in continuous safe braking distance. With sufficient distance, the following train is able to move closer to MRSP, and thus, this will reduce unnecessary dead time and enhance fluidity in traffic. On the other hand, when approaching stations or in congestions, decrease in speed is directly proportional to the behaviour of the leading train. The resulting trajectory has a more coordinated and efficient interaction between back-to-back trains.

Regarding system performance, all the supervisory curves are being transformed by Moving block signalling. As opposed to having each threshold tied down to a fixed infrastructure segmentation, it becomes a dynamic operation of real-time trains. This leads to increased regularity of motion, less variability of headway and an increase in line capacity. The legends (LC, WC, SBI, EBI, MRSP, speed) can be considered to illustrate the conversion of fixed spatial constraints to adaptive temporal spacing control by MB to maximize the throughput without compromising the safety integrity.

4.1.3 Positioning Results



Graph 3: Parameters influencing position output of both trains.

Position-time graph gives a spatially explicit representation of train interaction on the line and is one of the most important outputs to consider in order to assess system performance. The yellow curve is the position of the head of leading train and the blue curve is the position of tail in this plot. On the same note, the red curve marks the position of the head of the trailing train and the green curve the tail position. The physical train length is directly proportional to the vertical distance between the head and tail curve of any given train, and the horizontal and vertical distance between the two distinct trains would be used to describe the dynamics of time and space separation through the entire simulation horizon.

Kinematically, the gradient of each curve is the momentary speed. The steeper sections are acceleration or cruise, whereas the flatter ones are deceleration or station hold. The periodic drops of slope are the obvious manifestations of station stops since the head and tail paths are flattened and then the movement is restored. The regularity between these slope shifts across cycles is an indication of regularity of operations that is directly associated with consistency in motion and schedule compliance.

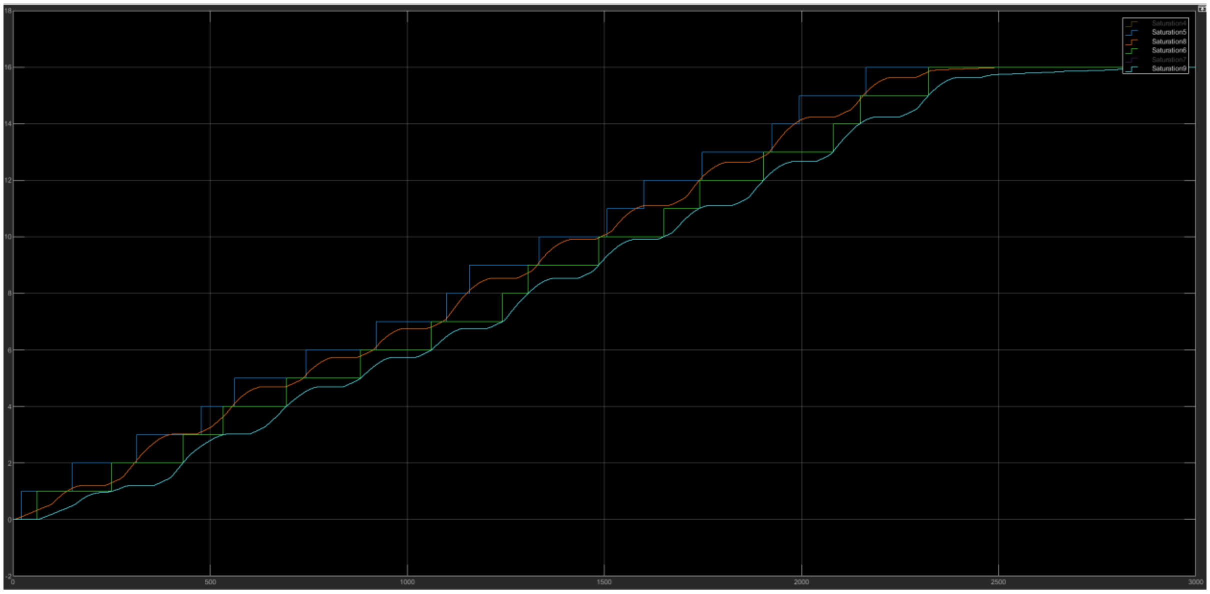
The performance data which is of the greatest importance, however, is the relative separation between the first and last trains (Daniel Knutsen, 2025). The temporal headway is the horizontal distance between the yellow and the red curves at any point and the spatial separation is the vertical distance between the curves at any moment in time. The importance of having a safe but a minimized separation is the cornerstone of optimization of line capacity. Separation is commonly discrete in Fixed block signalling since the occupancy of blocks is a constraint, but is more continuous in Moving block signalling, since it is computed using dynamic braking distance. Therefore, this position graph will be an immediate visual confirmation of signalling logic performance.

This graph helps to evaluate the motion ratio, commercial velocity, and line capacity in terms of Key Performance Indicators (KPIs). Motion ratio: This ratio, which is a ratio of running time to total time, may be concluded based on the length of sloped sections (compared to horizontal dwell sections). The total traveled distance can be divided by total simulation time to determine commercial velocity which is graphically shown by the position that is reached at the end of the time horizon. The more steeper the average slope of the whole journey the greater the commercial speed. Capacity of the line is directly correlated with the headway that can be achieved; the less unstable and small the gap between the red and yellow curves without breaking safety margin, the higher the volume of trains that can pass through per hour.

In addition, head and tail curves alignment makes block occupancy and movement authority calculations consistent. In case the trailing train head closes too much on the leading train tail the signalling system must interfere. The fact that there is no intersection of the curves proves safety integrity whereas the little but manageable spacing shows that there is efficiency in the use of infrastructure.

Thus, the position graph is not only a visual representation of kinematic but it is a complete performance evaluation instrument. It also justifies safety separation reasoning, operational stability, signalling efficiency, and throughput potential, so it is the focus of the quantitative evaluation structure of the thesis.

4.1.4 Block Occupancy Results



Graph 4: Parameters influencing block occupancy output of both trains.

The block occupancy graph is used to model the discrete movement of both trains through the infrastructure segmentation and gives a structural explanation of the way the signalling system controls the use of the tracks. Every step increase in this plot represents the entrance of a new block section of the train. The stair-case like design is typical of Fixed block logic, in which the infrastructure is broken up into a fixed number of segments and occupancy is updated only when the train head passes a block boundary.

The block index is indicated by the vertical axis, and time is indicated by the horizontal axis. The main train moves ahead and the block change takes place earlier in time than the back train. The staircase sequence in the trailing train advancement is by a steady time lag in accordance with the headway restriction. The distance between the two paths is a direct way of measuring the effectiveness of the signalling system to provide safe spacing and throughput.

This graph will be basically associated with the line capacity assessment. Block length and release logic limit capacity in Fixed block systems (Maksym Spiryagin, 2013). The back train cannot join a block until it is completely cleared by the front train (restrictions of release). Thus the horizontal distance between two successive staircase rises of the two trains is an indicator of the effective headway caused by the occupancy restrictions of blocks. Separations that are larger show signs of conservative block release and smaller capacity whereas tighter but stable separations show better use of infrastructure.

Block occupancy has an indirect impact on running time when looked at in terms of motion ratio. When the trailing train needs to wait until the block is released, enforced braking phases and prolonged dwell like conditions in-between blocks occur. This decreases the active motion fraction as compared to the total time of simulation. Therefore, the occasional or distant staircase changes to the train behind can be associated with deteriorated performance in terms of motion ratio.

There is also the impact made on commercial velocity. The commercial velocity will be calculated as the total distance/total travel time (Barbaro, 2021). The speed per block on a route is reduced when the entry into consecutive blocks is slowed by block occupancy constraints, although there may be no maximum speed changes. Hence, more compact and continuous block transition means an increase in the commercial velocity that can be achieved.

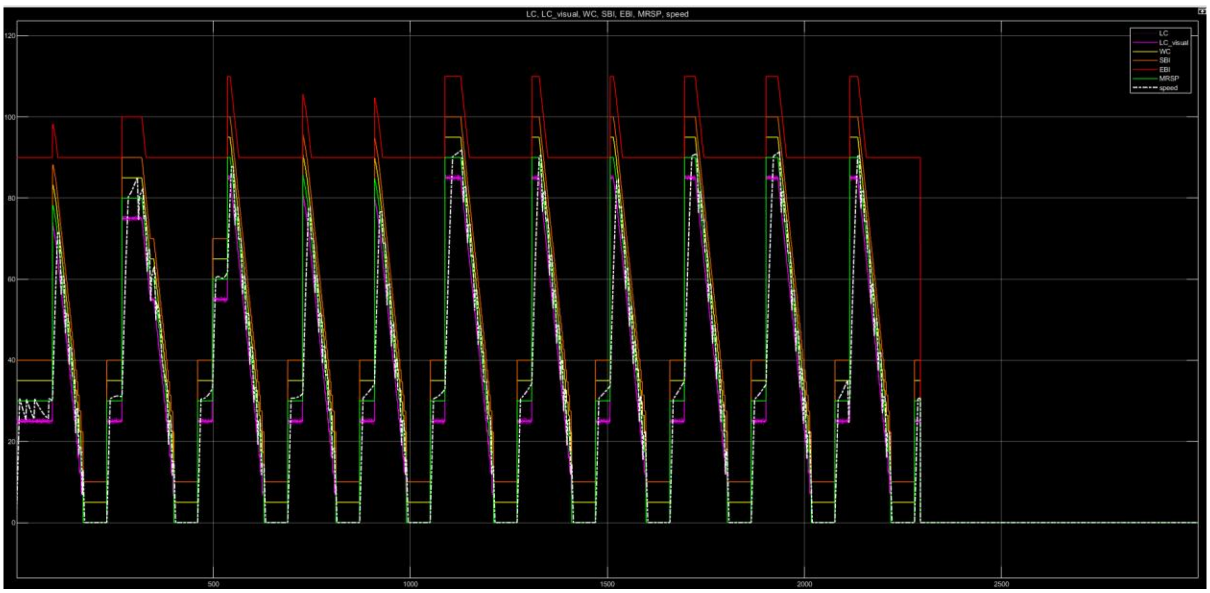
The graph is also a tool used to validate safety. The index of the trailing train block should never be and must never be at a level that coincides or surpasses the active protected zone of the leading train in any manner that is not consistent with safety margins. This offset between the two block trajectories is maintained, which ensures that the signalling logic does not allow deadly overlap. This staircase pattern in Moving block simulations would normally be less discrete or easier to smooth due to the fact that separation is calculated continuously as opposed to a fixed separation by infrastructure building boundaries.

To conclude, block occupancy graph is a measure of efficiency in the use of infrastructure. It is a direct indication of signalling limitations, practical headway regulation, safety margins and the overall effect of these on line capability, continuity in motion and business performance. To give a performance comparison between the Fixed block and the Moving block systems, this graph is one of the most concluding analytical instruments because it reveals the structural constraints of the discrete block segmentation.

5 Result Analysis

5.1 Fixed block Results

5.1.1 Leading Train Results



Graph 5: Leading train simulation environment results for Fixed block.

The first order (train behaviour) under the Fixed block simulation is based on the structural constraints of discrete block segmentation and the spacing of stations as opposed to the interaction with the preceding train. The leading train does not have a train ahead, therefore, the motion profile is controlled by the Maximum Regulated Speed Profile (MRSP), proximity to the station logic, braking curves, and the signalling thresholds (LC, WC, SBI, EBI). Having the maximum allowable speed of 160 km/h and total simulation of 3000 seconds, the attained speed profile exhibits a cyclical acceleration-cruising-braking behavior in line with a multi-station corridor.

During the start of the run, the first train speeds up towards the MRSP until it will come into contact with the first speed limit and approach to the station. The upper operational envelope is determined by the red MRSP curve. But the reality (white dashed line) can hardly be able to maintain long cruising at 160 km/h. This shows that the line formation, distance between stations and the braking effect will not allow it to work at the optimal speed that has been set. It does not do this, but the train gets to great speed, and then slows suddenly when it gets close to halting spots. This is a cyclical repetitive pattern which occurs in about every station interval.

The operational target of the driver below the MRSP is shown in the LC (Lower Curve) and LC vis visual curves. The real velocity varies about LC as opposed to MRSP, which proves that the driver model honors a conservative offset of the limit. Progressively stricter safety thresholds are defined by WC (Warning Curve), SBI (Service Brake Intervention) and EBI (Emergency Brake Intervention). When operating normally, the actual speed is higher than LC but less than WC and SBI. The lack of sustained EBI activation proves that braking interventions are anticipatory as opposed to reactive, and it proves that the braking model is properly tuned.

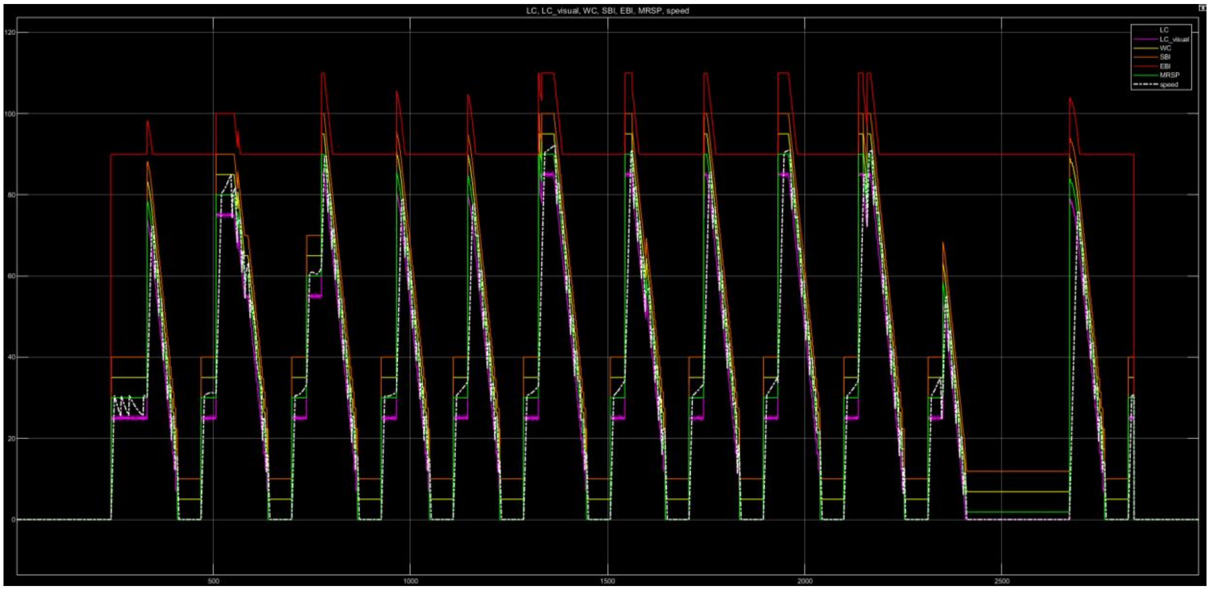
Since this is a Fixed block model, the first train does not have dynamic braking due to previous occupancy constraints. Its decreasing speeds are thus governed by geometries of infrastructure (stations and speed limits) and not signalling conflicts. This provides a reference level of performance against which the performance of the Moving block can be compared and against which the train operation can be compared.

Considering KPI, dwell times and braking phases are the key elements that determine the motion ratio of the leading train. Considering the presence of the full stops that occur multiple times in the speed profile, it is high the proportion of time spent at zero velocity. This decreases the ratio of motion especially in cases of thick station separation. The commercial velocity is thus significantly lower than the theoretical maximum of 160km/h. Approximate values of commercial velocity are total distance/ 3000 s; graphically, the number of braking cycles is frequent which shows that the average velocity is significantly less than the stipulated maximum.

The 240 seconds headway does not have a direct influence on the path of the leading train in Fixed block mode, as the train is not limited by another train. As an alternative, this parameter of headway dictates the time of injection of the following train. Thus, the profile of the leading train is the profile used as target: its acceleration capacity, braking range, and the pattern of the station dwell are the boundaries according to which the trailing train will have to work.

Overall, the results of the Fixed block leading train prove that there is no signalling-limited performance, but infrastructure-limited performance. The prevailing performance losses due to station halting cycles and braking limits, and not headway enforcing. This baseline is necessary to make further comparison with the dynamics of trailing trains and dynamic separation logic based on Moving block simulations, where further constraints on reachable speed and capacity are introduced.

5.1.2 Trailing Train Results



Graph 6: Trailing train simulation environment results for Fixed block.

The trailing train behaviour of the same Fixed block simulation conditions (maximum speed 160 km/h, headway 240 s, total simulation time 3000 s) shows the real limitations to operational performance of the Fixed block signalling architecture. In contrast to the leading train, the movement of the train is not infrastructure-paced, the motion of the trailing train is highly limited by the presence of blocks and the safety distance implied by the Radio Block Centre (RBC).

The overall acceleration-braking pattern looks like the one of the leading train at first sight. The truncation of the speed envelope is however the major difference. The slow moving train never hits the same peak speed as the first train even when the MRSP (red curve) would permit higher velocities. The real speed (white dashed line) often crosses the LC and WC curves at earlier and is constrained at the lower side of the MRSP. This is not a vehicle restriction but rather a constraint imposed on signalling.

In a Fixed block mode, the movement authority (MA) is awarded block-by-block. The last train should not be allowed to pass into the line unless the train before it has cleared a full block and then an extra safety margin. This generates repeated braking intervals other than station-induced but signalling-induced. The oscillatory peaks in the speed are also a bit lower and more compressed compared to those of the leading train, and this means that the block boundaries cause premature braking, not the optimum energy-based braking.

LC (Lower Curve) indicates the target speed of operation that is lower than the MRSP. In the case of the trailing train, LC is often pulled down sooner before the front train. Intervention thresholds are determined by WC, SBI and EBI curves and though the emergency braking is not used, the closeness of the real speed to WC/SBI shows a tighter control because of the lesser movement management power. The initiation of braking happens sooner in multiple cycles, which proves that the logic of separation, rather than infrastructure geometry itself, rules movement.

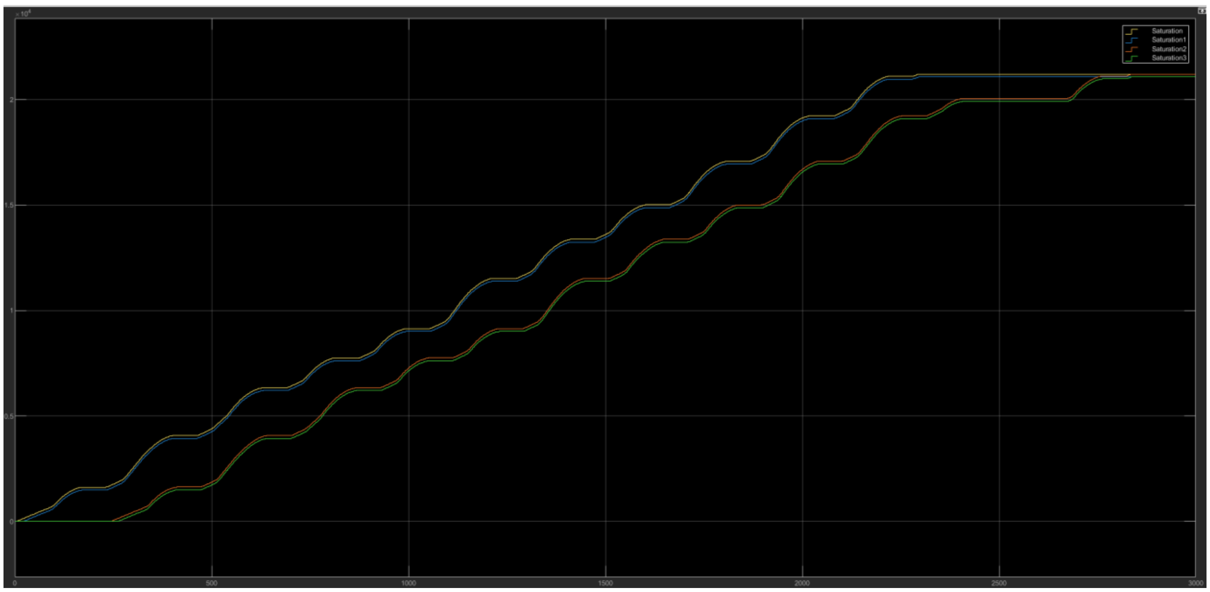
Here the effect of the 240 seconds headway comes in. The discrete nature of block release results in quantisation effects although headway is constant. The train in the procession is not able to take advantage of unused free space in partially cleared blocks. Thus, signalling logic does not allow full acceleration even though the physical separation may be adequate. This structural drawback of Fixed block systems is this inefficiency.

In terms of KPI, the ratio of motion between the trailing train and the leading train is less than the leading train. Further acceleration and forced speed limits elevate the amount of time in constrained or deceleration momenta. Commercial velocity thus becomes lesser compared to the first train, despite both of them running under the same maximum speed and infrastructure conditions.

However, the most serious, line capacity under Fixed block is directly associated with this behaviour. Since the authority of movement is given discretely and conservatively, the trailing train will not be able to achieve a profile of speed that makes complete use of the braking distance available. This adds to high effective headway than 240 seconds of nominal usable capacity. The outcome is low utilisation of track space and throughput.

In brief, the trailing train Fixed block results are a clear indication of degradation in capacity due to block segmentation. Signalling constraints artificially compress the speed envelope, rather than traction limits or the design of the infrastructure. This will be a quantitative base with which to compare the operation of Moving blocks where dynamic continuous braking curves are supposed to limit these inefficiencies and improve commercial velocity and line capacity.

5.1.3 Position Results



Graph 7: Both trains position while each time step update during Fixed block simulation.

This plot of position versus time gives the best physical explanation of the Fixed block behaviour with a headway of 240 s and a maximum speed of 160 km/h. In contrast to the speed graph that emphasises dynamic thresholds and braking envelopes, the position graph clearly represents spatial separation, train interaction and efficient use of infrastructure over time.

The yellow and blue curves are used to show the head and tail of the first train respectively and the red and green ones show the head and tail of the second train respectively. The distance between the yellow and red curves at a given time is the distance between the yellow and red lines that increases vertically which is associated with the headway distance at the given time. More to the point, the horizontal movement of successive inflection points demonstrates the spread of signalling constraints within the system.

The discontinuity of the routes is representative of the station stops and acceleration-braking cycles. The increasing segments are associated with acceleration and cruise and the flat or slightly rounded segments are associated with dwell or constrained motion periods. The repeating pattern affirms cyclic spacing in the stations and uniform behaviour of operation.

The most acute finding is the situation when a constant spatial displacement between the trajectories of the leading and trailing trains is observed. The nominal headway is 240 seconds, but the spatial separation does not occur in a constant manner. It stretches and retracts in accordance to the braking and acceleration cycles put in place by Fixed block logic. The following train never smoothly approaches the braking envelope of the preceding train. Rather it uses block release logic to maintain a conservative spatial buffer.

Three important performance indicators in this spatial buffering are directly affected:

First, motion ratio. The more continuous and gentle the slope of the position curve the greater the fraction of time in productive movement. The trailing train in Fixed block has even more irregular slope transitions, which points to more constrained phases and less effective motion ratio.

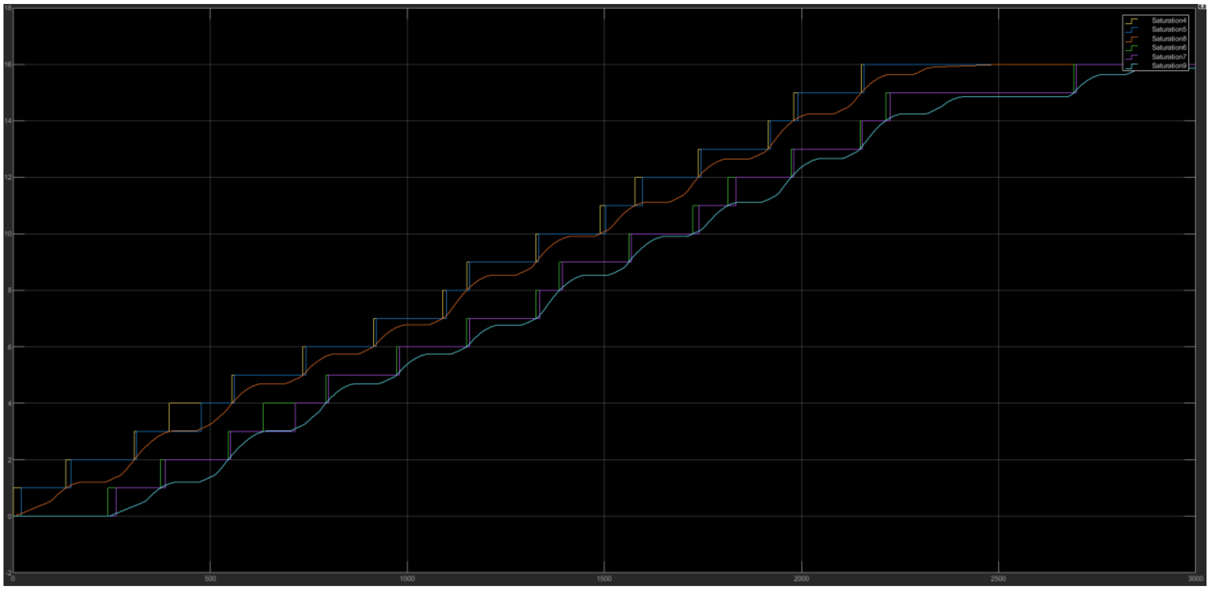
Second, commercial velocity. The commercial velocity is calculated as the sum of travelled distance/sum total of the simulation time taking into consideration the effects of dwell and constraint. Since the trailing train undergoes premature braking and tardy acceleration as compared to the leading train, its position curve falls progressively behind. The overall effect is that it decreases its mean gradient with time, thereby, decreasing commercial velocity.

Third, line capacity. The basic determinant of capacity is the minimum sustainable headway. In the position graph, the curves of red and yellow do not tend towards each other with a continuously adjusting distance. Rather, they are quantised spaced reflection by discrete block occupancy. This supports the fact that Fixed block signalling imposes structural separation to the requisite of pure braking distance. This leads to underutilisation of infrastructure in optimum theoretical efficiency.

Also, the ultimate convergence of curves at the end of the simulation indicates the terminal boundary condition as the two trains are coming to the end of the line. Safe separation enforcement during the simulation is ensured by the lack of overlap.

Overall, this position graph confirms that on a Fixed block signalling system, the spatial separation is controlled by discrete block clearance and not braking curves. The moving train is not able to utilize dynamic spacing in the real time, which results in conservative separation distances. The result of this behaviour is a direct decrease in motion ratio, decrease in commercial velocity, and a decrease in line capacity as compared to the same under a Moving block system.

5.1.4 Block occupancy Results



Graph 8: Both trains block occupancy while each time step update during Fixed block simulation.

This block occupancy graph is a graph that shows the discrete infrastructure use of the line in Fixed block signalling. This plot contrasts the train movement into block-occupied resources, unlike the position graph, which demonstrates the continuous spatial movement. The difference in steps between the entrance of a train head into a new Fixed block is the same as the difference between the release of a block once the train tail leaves it.

Fixed block segmentation effectively results in the staircase profile. The horizontal plateaus signify that the train stays in a particular block. The vertical leaps indicate the change of blocks next to each other. Since blocks are discrete units of infrastructure, the signalling logic only allows occupancy to take place after the occupancy of the prior block by the tail of the preceding train. This is the reason why the block index of the trailing train will always be lower than the block index of the leading train at least by one block.

Of particular concern is the distance between the two trains in number of blocks. Although the braking curves could permit a smaller safe dynamic distance, there is a

Fixed block logic that stipulates that there must be at least a certain number of empty blocks between trains. This adds topology based structural capacity constraints not so much physics based. It is graphically confirmed that there are several blocks that are not occupied in between the front and the back trains throughout most of the simulation.

This has direct implications as far as KPI is concerned:

First, line capacity. Block length and block release logic are the basic way in which capacity is constrained by Fixed block systems. The graph shows that the trains can only move forward as soon as the one behind them comes into play and creates a quantised utilisation pattern. Due to the relatively long distance between blocks in comparison with the distances of dynamic braking, infrastructure is not fully used. This decreases the highest possible train frequency.

Second, headway enforcement. The 240-second headway is manifested in the uniform deflection between the two block tracks. But effective spatial headway can easily exceed the level of braking safety that is strictly required. This conservative margin is measurable using the block occupancy graph.

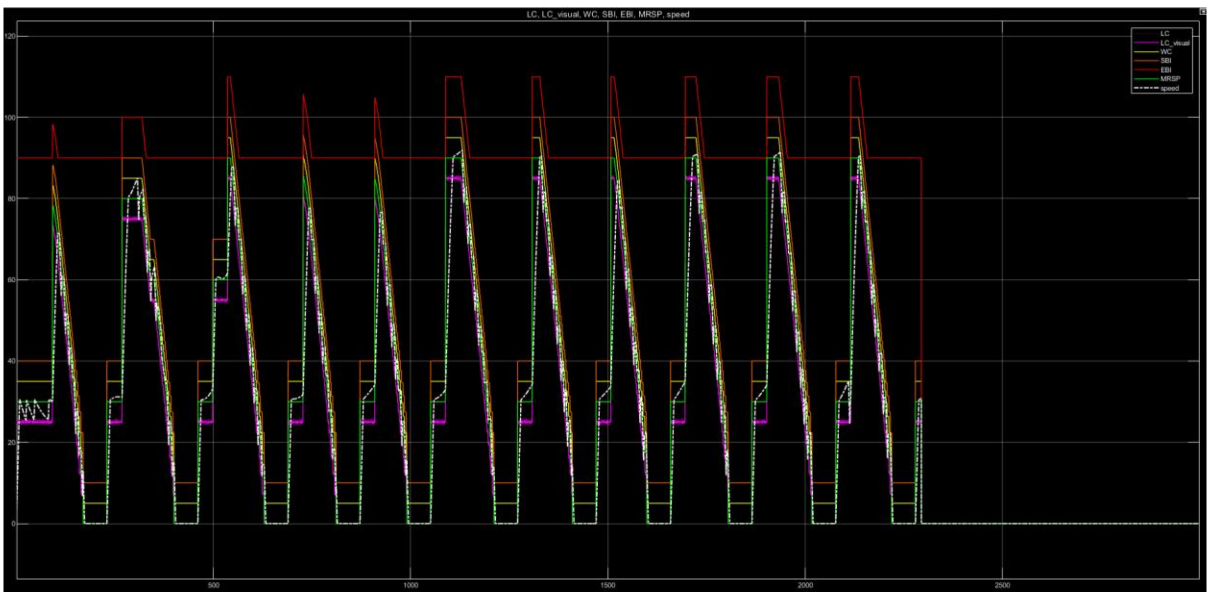
Third, efficiency of utilisation of infrastructure. Ideally, the high capacity systems reduce the block time that does not have an occupation. The duration on which each block is idle in this graph is measurable after one train has cleared the block but before the other train enters it. This wasted time is wasted potentiality. The braking distance is short compared to the block length and the longer the block length, the larger this inefficiency.

Fourth, motion continuity. Since the following train has to watch until it is to pass the block, but not to constantly adjust its braking profile, the slugging-retraction cycles are more pronounced in the acceleration-braking cycles of the following train. This has the effect of directly decreasing motion ratio and significantly reducing energy consumption as a result of repetitive traction-brake transition.

In short, this block occupancy graph gives structural evidence on the limitation of block capacity constraints. It visually illustrates the way that discrete block segmentation controls the separation of trains, limits dynamic following behaviour, and inserts inherent efficiencies of capacity. The following graph will hence be instrumental in determining the difference between Fixed block and Moving block signalling performance of your thesis analysis.

5.2 Moving block Results

5.2.1 Leading train Results



Graph 9: Leading train simulation environment results for Moving block.

Even in the case of Moving block signalling, although the maximum permissible speed (160 km/h), time duration of the simulation (3000 s), and nominal headway (240 s) are constant, this case should be interpreted differently than that of a Fixed block case.

On the face of it, the LC (Line Capacity limit) and WC (Warning Curve), SBI (Service Brake Intervention), EBI (Emergency Brake Intervention), MRSP and actual speed curves look like the Fixed block scenario in terms of structure. Nevertheless, the most important difference is in the way the allowed range of speeds changes with time.

The discrete segmentation of infrastructure is no longer relevant to the protection limits in Moving block operation, but rather calculated by dynamic train separation determined by continuous radio-based communication. It implies that the speed profile of the leading train is not limited by block release logic but by only its braking performance envelope and infrastructure limits.

The MRSP (red curve) has a maximum of 160 km/h as the infrastructure maximum in this graph, which is not interrupted by some artificial block boundary. The lack of stepwise limitations in the allowed speed hierarchy means that the one that leads the train is subjected to a less abrupt enforcement changes between LC, WC, SBI, and EBI limits. Its braking curves are continuous and physics-based, as opposed to being block length discretised.

The speed curve thus will have more regular acceleration periods and more regulated deceleration patterns towards stopping positions. The peaks are more pristine and the speed recovery between cycles is not so distorted by upstream signalling constraints. This is a direct demonstration of the underlying principle of Moving block systems that the separation is calculated not by an integer number of blocks but by a continuous safe braking distance.

There are a number of implications, as far as KPI is concerned:

First, motion ratio improves. Since the leading train is not affected by any unnecessary restrictive signal aspects created by a discrete block occupancy, it then has a greater fraction of time with a high propinquity of the maximum allowable speed. The acceleration-braking swing oscillations depend entirely on operational stops, and not on infrastructure segmentation.

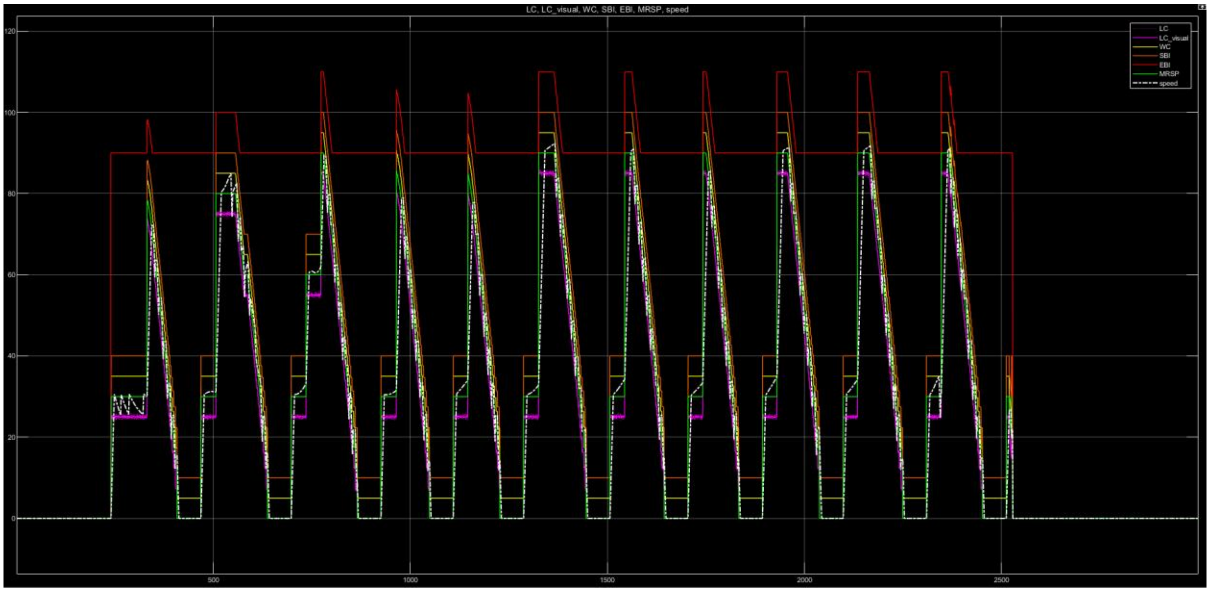
Second, the speed in commercial is raised. As the commercial velocity is an artificial constraint of the total time divided by the travelled distance without the stops, the smoother speed envelope and lower artificial speed limits decreased the effective running time between stations.

Third, there is improved efficiency in the use of infrastructure. Although this is the leading train, its behaviour determines reference to other trains that follow. Under Moving block the train in front keeps on moving, allowing the train behind to come closer without having to wait before the first block is cleared. The dominant train thus indirectly endorses increased line throughput.

Fourth, safety margins are optimised dynamically. There is a close supervision, hence safe and tight, coverage of the actual speed profile by the WC, SBI and the EBI curves. This is in contrast to Fixed block, where the safety distance is excessively estimated due to block granularity, in Moving block, the braking distance is computed using the real-time position and deceleration capability.

In short, this Moving block simulation graph of the leading train shows the structural superiority of continuous separation logic. The train works nearer to its performance limits, and less artificial limitation is introduced, resulting in superior motion regularity, increased commercial speed, and increased theoretical line capacity.

5.2.2 Trailing train Results



Graph 10: Trailing train simulation environment results for Moving block.

This is the trailing train graph that follows Moving block signalling and the actual performance difference is clear in this case. The dynamic safety envelope is determined by the leading train, but is shown by the trailing train as to the efficiency of the envelope utilization.

The Moving block environment does not have the trailing train wait until a complete Fixed block is cleared. Rather, its allowed speed is recalculated on a continuous basis, using the position and braking capacity of the train in the lead. Consequently, the MRSP (red curve) and the supervision limits (LC, WC, SBI, EBI) develop dynamically, but not in stages.

The most significant thing that can be seen in terms of the graph is that the accelerating train accelerates at a younger stage and the speeds are sustained at significant lengths than in the Fixed block scenario. The braking stages are less shocky and abrupt as the movement authority is not limited by block boundaries. The speed envelope is only decreased when the safe braking distance to the leading train truly needs it, as opposed to the artificial reduction of the permitted speed caused by block occupation.

The LC, WC, SBI, and EBI curves follow the profile of the actual speed closely, which means that the train does not work at the edge of the supervision with unnecessary conservativeness. This implies that the system is tight but not restrictive. There are still oscillatory speed behaviour because of station stops and working cycles but the amplitude and timing of the speed drops are determined by physical separation and not infrastructure segmentation.

The implications are of great significance, as far as a KPI is concerned:

To begin with, there is an increase in motion ratio of the trailing train. The time at low speed or on forced braking which is caused by signal constraints is decreased. More productive movement is made around the MRSP.

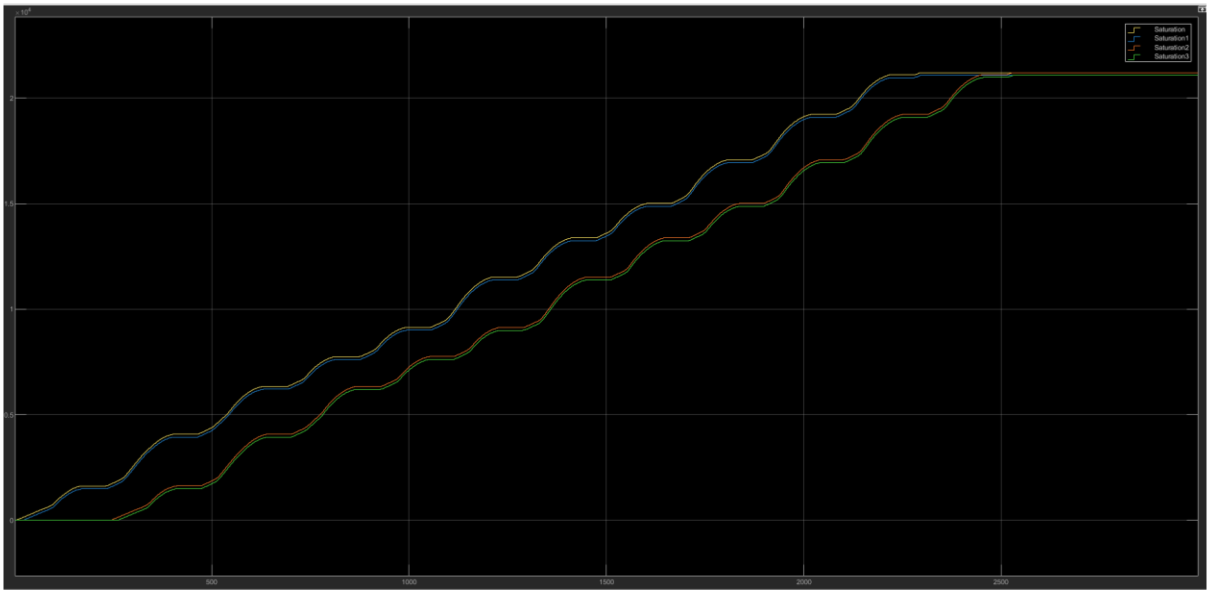
Second, there is increased commercial velocity. Since the distance between the trains can be reduced more effectively by the trailing train, the overall travel time will be reduced without affecting the safety. The productive time interval between stops is not long.

Third, there are enhanced utilisation efficiency of the headway though the headway is still 240 s nominally. In Moving block, the block length does not control the theoretical minimum headway but the dynamic braking distance controls it. This yields less track-space to waste and more line throughput capacity.

Fourth, there is an increase in line capacity potential. Achievable headway has an inverse relationship with capacity. Although you might continue with operation of 240 s, the system shows that it would be possible to operate at a lower stable headway without committing any safety violation. It is the structural advantage of Moving block.

Overall, this trailing train diagram is a confirmation that the Moving block signalling eradicates the inefficiencies created by inflexible division of infrastructure sections. The train is driven nearer to its dynamic safety limit, which enhances the regularity of motion, commercial velocity, and effective line capacity whilst preserving complete braking supervision integrity.

5.2.3 Position Results



Graph 11: Both trains position while each time step update during Moving block simulation.

This state diagram of the Moving block simulation is the most convincing structural evidence of dynamic signalling restructuring train interaction.The curve of yellow color in this diagram depicts the leading train head and the curve of blue color depicts the tail. The red curve is the head of the tail train and the green curve is the tail of the tail train. The curves indicate the instantaneous speed of the slopes, and the absolute distance between the trailing head (red) and leading tail (blue) the distance of actual dynamic separation imposed by the signalling logic.

The distance between the trailing head and leading tail is not quantised in stepwise or man-made steps as in Fixed block behaviour. The division is gradually developed. The following train does not wait until the leading train finishes its block release, but instead it maintains the distance with the actual braking envelope of the leading train in real-time. This creates a clearly smaller yet safe spacing pattern.

This is because of the near parallelism as the curves move towards cruising stages and this indicates velocity pre-alignment. The following train quickly becomes aligned on the dynamic safety limit after which it follows the preceding train with a small margin of excess spacing. The fact that there are no large horizontal differences between successive acceleration phases proves that wastage of idle time is eliminated.

This graph supports three performance indicators directly, concerning the KPI perspective:

To start with, there is an enhancement of effective utilisation of headway. The nominal headway is still 240 seconds, but there is greater utilisation of the space on the line. The following train takes up the track segments previously since it is not holding back on block clearance. This minimizes unused infrastructure capacity.

Second, there is an increase in motion ratio. The less bumpy convergence, and the reduced dwell at restrictive distances, result in a less forced operation at low speed due to signalling constraints. The proportion of the productive motion time with regards to the total journey time is enhanced.

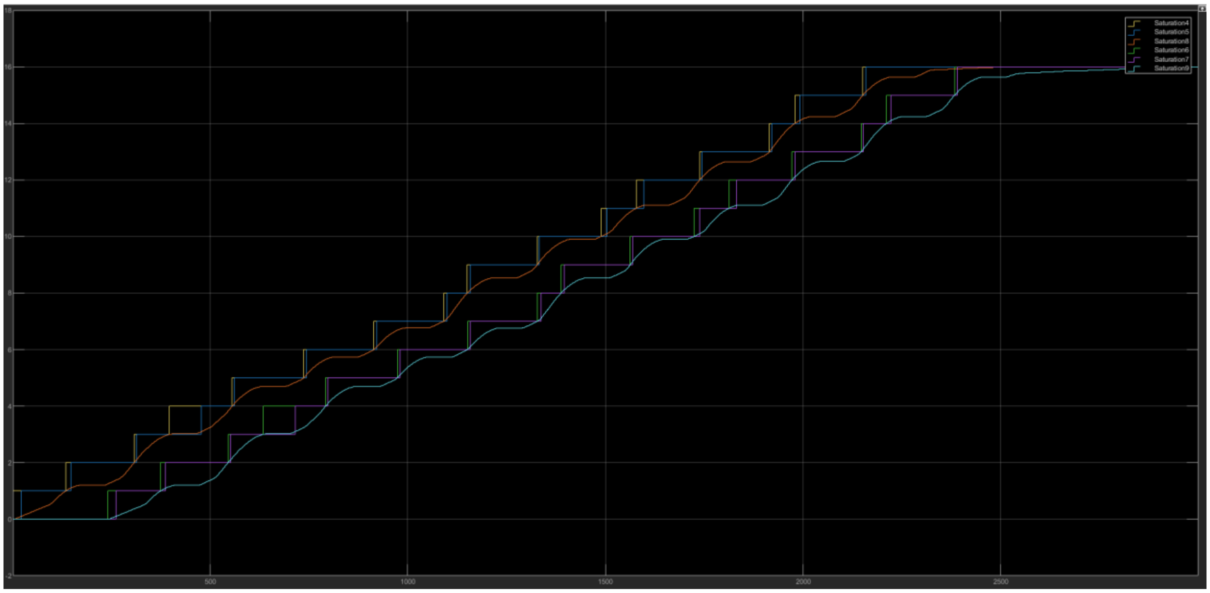
Third, business speed is enhanced. Due to the fact that the trailing train is allowed to dynamically close the gap, the total trip time decreases but does not increase the maximum speed. This is not because there are increased infrastructure limits, but improved spacing logic.

Fourth, the potential of capacity of line is raised structurally. Capacity is based on minimum safe distance. The physics of braking controls the separation in Moving block rather than block length. The lower mean distance between the red and blue curves shows that a more significant number of trains could theoretically be placed within the same line without affecting the safety situation.

Above all, the graph illustrates stability. There exist no oscillatory amplification effects, no follow distance instability and no safety envelope violation. The system works as a well-damped follower model which confirms both the braking curve computation and RBC logic.

Concisely, this plot position proves that the separation control is no longer infrastructure based segmentation but physics based dynamic control, by Moving block signalling. Increases in motion regularity, commercial speed, and possible line capacity, are the result of that shift as the fundamental mechanism.

5.2.4 Block Occupancy Results



Graph 12: Both trains block occupancy while Moving block simulation.

This Moving block simulation block occupancy graph shows the effect of the distance between the infrastructure utilisation in conditions where distance control is not limited by fixed spatial segmentation.

The shaded numbers in the diagram of figure below indicate the occupancy of each virtual protection segment of the respective train section (head or tail). In comparison with Fixed block signalling, when occupancy transitions are determined by Fixed block boundaries, Moving block graph transitions are more continuous and smooth. The intervals between the tracks are closer together in time and the discharge of track behind the front train also takes place earlier than its movement.

The most important one to note is the minimization of inactive infrastructure periods. In Fixed block systems, a complete block is held until the rear of the train has cleared it completely, although in practice the braking distance would permit it to be used again. Conversely, the Moving block occupancy curve indicates that the real-time braking bracket is dynamically connected to the track release. When the condition of safe separation has been met, the trailing train is allowed to extend its movement authority. This creates a more efficient and congested occupancy staircase.

Regarding performance, this graph has a direct impact on the key KPIs:

To begin with, there is improved infrastructure utilisation. The occupancy rates move in shorter time rates i.e. track resources are reconnecting faster. There is no artificial demarcation of the line by Fixed block lengths, but occupation is controlled by physical braking limits.

Second, there is enhanced structural capacity scaling. The basic factor in determining capacity is the safe time span with distance between trains. The decreasing horizontal separations between the occupancy increments in this graph show that the shorter the infrastructure length, the closer the train succession. Although, in your simulation, the nominal headway would be 240 seconds, the dynamic release behaviour shows that headways would still be practicable without breaching the safety constraints.

Third, there is an improvement of motion regularity indirectly. Since the process of releasing occupancy is not as step-based or coarse, the train behind will not receive so many sudden extensions of authority. This lowers the oscillatory acceleration-braking cycles in comparison to Fixed block behaviour and stabilises the resultant dynamics.

Fourth, commercial velocity is enjoying short restrictive periods. As the movement authority grows, the train that is in track spends less time under restrictive speed prerogative due to movement block only. This means that the average effective speed along the corridor increases without changing maximum permitted speed (160 km/h).

Above all, this graph substantiates the conceptualization change of infrastructure-determined capacity to physics-determined capacity. Block is the restrictive unit in the Fixed block. The form of braking distance becomes the limiting factor in Moving block. The occupancy graph shows that after the virtualisation of segmentation, the line acts as a continuously reusable resource as opposed to a chain in hard compartments.

The Moving block occupancy behaviour that is demonstrated here justifies the anticipated augmentation of the potential of line capacity, the ratio of motion, and commercial velocity. The bottleneck is no longer the infrastructural model--the braking model is. This difference is the focus of your thesis on comparing the fixed and Moving block signalling systems.

6 KPI analysis

6.1 Commercial Velocity

The commercial velocity was also obtained by the ratio of the total distance of the corridor (21 km) and the time that it took to make the trip. The Leading train takes about 2500 seconds to cover the corridor making its commercial velocity 30.2 km/h.

In the case of the trailing train running on Fixed block signalling the departure time is 240 seconds and the arrival time is about 2900 seconds, which provides a commercial velocity of 28.4 km/h and a 2660 seconds travel time after neglecting each dwell time in the route.

Under Moving block signalling, the trailing train in the simulation takes a journey of about 2700 seconds. That is a travel time of 2460 seconds without considering the dwell time and a commercial velocity of 30.7 km/h.

This is nearly a 2.3 percent enhancement in commercial speed when Moving block signalling is utilized. This is not done by increasing the maximum speed that does not exceed 160 km/h but by making the dynamic separation management more efficient, eliminating unjustified restrictive phases and providing a flow of less sporadic trajectories.

6.2 Motion Regularity

The Motion regularity of the trailing train was computed based on its actual running time and not the entire 3000 seconds of simulating horizon. The trailing train starts moving at about 240 s because of the headway that is imposed. Under the Fixed block scenario the train takes about 2900 s to complete the journey providing a successful operating time of 2660 s. The total stationary period recorded in the speed time graph is about 790 s which gives a regularity of motion of 0.70.

The Moving block simulation results in the trailing train finishing its run sooner at about 2700 s resulting in an operating time of 2460 s. The stationary time measured was approximately 645 s, and the result gave a motion regularity of 0.74. This is close to a 4 percent improvement in motion regularity when under Moving block signalling. The enhancement is due to the decrease in idle time and the ease of transition between movement authority related to continuous separation logic.

6.3 Line Capacity

The difference between the actual arrival time of the leading and trailing trains in the terminal position was used to obtain the effective line capacity. Even though the nominal departure headway was to be 240 seconds, the actual headway varies as a result of signalling constraints. The Fixed block simulation model estimates the leading train to reach the terminal position at an initial time of about 2500 seconds, and the trailing train reaches the terminal position at about 2900 seconds which leaves an effective headway of 400 seconds. This is equivalent to a working capacity of 9 trains per hour.

Comparatively, with Moving block signalling, the following train is scheduled to arrive after about 2700 seconds and yields an effective headway of 200 seconds. Effective capacity is 18 trains per hour correspondingly. Thus, a 100 percent increase in effective line capacity with Moving block operation versus Fixed block operation on the same nominal headway conditions is observed.

The outcome of this experiment shows that theoretical capacity as determined by departures headway can be the same but that practical capacity is greatly affected by signalling philosophy and separation logic.

7 Further Improvements

7.1 Difficulties faced during simulation

7.1.1 Challenges Encountered During the Research Work

Along the way of the thesis work, the framework of the simulation was developed and validated, which had a number of technical and methodological challenges to overcome. A major challenge was to maintain consistency between the signalling concepts on theory and their application in the MATLAB-Simulink® environment. The combination of Fixed block and Moving block logic had to be well synchronized in vehicle dynamics and braking curve calculation, and the movement authority. The introduction of numerical stability and compatibility with real-time execution added further complexity especially in trying to synchronize the solver configurations, sample times and hardware-in-the-loop interfaces. Additionally, to derive meaningful performance metrics like regularity of motion, commercial velocity and efficient headway, it was important that simulation results were strictly interpreted and that the computation of result was done using actual operating time and not nominal simulation time. The setup of communication between the embedded hardware platform and the host system also required an iterative debugging process, particularly in the area of deterministic data communication and synchronization. These problems required many validation cycles, parameter searches, and structural model adjustments before a stable and analysis consistent simulation space was obtained.

7.1.2 Hardware Integration Challenges and Raspberry Pi® Malfunction

Another issue that arose in the experimental stage was the incorporation of the Raspberry Pi® as an external computing unit in the real-time simulation environment. The theoretical architecture was a sound one, however, in reality, when implemented, it had instability problems, with connectivity, synchronization, and system configuration. The Raspberry Pi® sometimes did not reconnect to the MATLAB® Setup Manager although it was available in the network. The main causes of these problems were found in the inconsistency of IP configuration, firewall limitations, difficulties in SSH authentication, and the intermittent Wi-Fi unsteadiness. Certainly, in certain instances, the SD card configuration was corrupted or the firmware was quite old and caused communication rejection on the required ports. These failures emphasized the vulnerability of distributed real-time systems to network-layer dependencies and hardware-level reliability. In contrast to pure software simulations, hardware-in-the-loop systems add external uncertainties that have to be addressed by means of deterministic configuration control and strict network validation.

7.1.3 Driver Behaviour Modelling Limitations

The driver behaviour used in the simulation was a theoretical model on the probabilistic aspect of reaction time which included parameter like reaction time, aggressiveness coefficients and braking utilization factors. In as much as this abstraction grants the ability to conduct controlled experiments and replicate these experiments, it also simplifies the human variability in the real world. In reality when operating on the railways, fatigue, environmental factors, clarity of the signalling system, and real time situational awareness affects the response of drivers operating within the system. The theoretical driver model bases itself on deterministic reaction intervals and limited variability, yet the response of drivers in real life could be quite inconsistent with predicted thresholds. Therefore, although the simulation reflects the overall trends in the system and the relative performance differences among signalling philosophies, it is not a complete reflection of behavioural unpredictability in live operations. This restriction is especially applicable to be applied to the dynamics of safety margins and braking response timing.

7.1.4 Sample Time Configuration and Real-Time Execution Issues

The other problematic challenge that was encountered was the sample time management in the simulink® real-time environment. Variable-step solvers and asynchronous block execution can be used simultaneously in the offline simulation without this instability. Nonetheless, in real-time implementation, determinism and the use of similar sample time settings are very strict. The incompatibility of sample rates between subsystems led to multi-task execution error and non-deterministic behaviour errors. This was more pronounced in case of integrating enabled subsystems and communication blocks. In a hardware-in-the-loop architecture, irregular sampling periods also may lead to data overruns, missed deadlines, and timing jitter, and eventually the failure to synchronize computational units. To have stable execution, it was necessary to enforce discrete solvers, sample times between subsystems to a common base rate, and to provide single task execution within key modules.

7.1.5 UDP Communication and Data Exchange Constraints

The use of UDP based communication between the host PC and Raspberry Pi® also presented further technical complications. Although UDP provides low-latency data transfer and is therefore more appropriate in real-time applications, it cannot guarantee the delivery and order of packets. In testing, misaligning of data was caused by the misconfiguring of data size, scalar-versus-vector mismatch, and port assignment inconsistency. The receive block was in a number of instances giving a zero value because of data type mismatch or wrong interpretation of the received bytes. Moreover, in UDP communication, it is important to strictly coordinate the time of the send and receive samples, or the packets will be dropped or overwritten before they can be processed. These concerns highlighted the significance of deterministic packet architecture, uniformity of datatype and network stability within distributed simulation architecture. Distributed execution has a much larger complexity and overhead in system behavior and debugging compared to pure local simulations.

7.1.6 Overall System Integration Complexity

Signalling logic, the dynamics of vehicles, and real-time constraints on executing the logic, combined with hardware communication, created a multi-layered system in which faults in one layer were passed on to others. There was no formal exercise like theoretical modelling, unlike the practical implementation; solver settings, communication interfaces, operating system settings, and numerical stability had to be constantly verified. The shift to a somewhat hardware-integrated platform with more-or-less simulated environment demonstrated the existing disconnect between the conceptual design system and its actual implementation. It took several rounds of debugging, re-calibration of parameters, and modification of structural models before a reliable and analytically sound framework of simulation was reached.

7.2 Route Analysis

The next logical extension of this study is the test of the created simulation model to a real operating railway line, namely the high-speed line of Milano-Bologna. This is one of the most essential sections of Italian railway system, which has great traffic flow, mixed traffic, and performance imperatives. This is because expanding the current model to this corridor would be able to provide a complete analysis of both the Fixed block and Moving block signalling performance in realistic infrastructure and operational condition.

An extension like this would entail the incorporation of realistic line geometry, gradient profiles, data of speed restriction, station spacing, and timetable parameters into the simulation environment. With the help of the model calibration with the parameters peculiar to the corridors, there would be an opportunity to measure the improvement of commercial velocity, regularity of motion, and an effective line capacity in the context of a real situation. Moreover, this would enable the evaluation of the dynamic separation logic performance in the presence of heterogeneous traffic conditions, such as trains types, dwell time, and perturbations in operations.

Even though such a route-level implementation was not finished in time during the scope of the current thesis, the designed architecture has been designed in such a way that it is modular and scalable. The signalling logic, braking curve calculation and movement authority modules can be directly reconfigured to the data values in the corridor. In turn, the Milano-Bologna application is not an attempt of conceptual extension, but a viable step toward industrial validation and strategic infrastructure planning. Such a work in the future would fill the gap between theory of performance comparison and applicable operational optimization strategies of high-capacity railway systems.

7.3 Other Real-time simulation methods

Although the current study utilized a MATLAB-Simulink® architecture and Raspberry Pi® assisted hardware-in-the-loop (HIL) to integrate additional hardware with the simulation core, a variety of other real-time simulation tools and platforms might be used to expand or industrialize the framework.

The application of dedicated real-time target machines is one of the established methods like speedgoat® systems. In contrast to embedded microcontrollers, the Speedgoat® platforms have been developed with deterministic real-time execution and fixed-step solver performance guaranteed. These systems can support the FPGA acceleration, high-speed I/O interfaces and the capability to do high-speed synchronization and are therefore appropriate in the validation of large-scale railway control. Such platforms are more stable in computing, less latent, and more industrial-duty than the integration of Raspberry Pi®.

The other option is the use of real-time simulators of OPAL-RT, which are commonly used in power system and rail traction research. Such systems enable redistribution co-simulation with hardware controllers and multi-core deterministic processing. In signalling, OPAL-RT might be applied to simulate track circuits, interlocking logic or braking systems with a greater fidelity and parallel processing.

In the case of distributed simulation architecture, UDP-based communication can be substituted by ROS (Robot Operating System) or DDS (Data Distribution Service) frameworks. These message handlers have structured message handling, time synchronization and better fault tolerance. UDP is low in latency but does not guarantee delivery or control synchronization. The communication would be robust in the complex multi-node simulation of signalling using DDSes.

The other possible method is the co-simulation based on FMI (Functional Mock-up Interface) standards. FMI enables the integration of various simulation environments (e.g. MATLAB®, Modelica® or even railway-specific simulation tools like OpenTrack®) into a common execution model. This would enable the infrastructure modelling, timetable simulation and dynamic braking computation to run in distinct specialized surroundings with synchronization of execute.

In the case of driver modelling, the probabilistic theoretical driver abstraction would be substituted by integration with machine learning-based behavioural models. More realistic variability of responses under dynamic signalling conditions could be simulated by reinforcement learning agents or stochastic behavioural models.

Also, hardware acceleration using FPGA might be implemented in the braking curve calculation and movement authority logic. Because braking curve generative algorithms are computationally expensive in dense situations, hardware-based acceleration would decrease response time and enhance predictability in safety-critical validation environments.

Digital twins based on clouds are also a current extension. The signalling model can be realised in a digital twin on a cloud-based environment to enable real-time monitoring, forecast analysis and remote validation of several simulated corridors, rather than deploying a localised HIL set up.

Relative to these industrial grade solutions, the existing implementation based on Simulink® and Raspberry Pi® is a cost-effective prototyping solution. It enables verification of signalling logic, KPI analysis and dynamic behaviour analysis with low infrastructure cost. Deployment in safety-critical certification environments, however, would need deterministic platforms, including Speedgoat®, OPAL-RT®, or acceleration by FPGAs, to offer a better execution environment with respect to stability and scalability.

The flexibility of the designed simulation framework due to its modularity will guarantee compatibility with the advanced real-time platforms and distributed architecture. The basic signalling logic, braking curve algorithms, and KPI evaluation techniques can be ported to advanced grade industrial real-time platforms although the hardware used to implement them was available off-the-shelf and based on MATLAB®. As a result, the study creates not only a comparative analysis of Fixed block signalling and Moving block signalling but also a scalable basis of real-time validation of the railway system in the future.

8 Conclusion

This thesis gave a comparative analysis of Fixed block and Moving block railway signalling systems in a comprehensive way by establishing a modular simulation framework that was run in MATLAB-Simulink® and extended to a real time performance. Their main goal was to assess the impact of signalling philosophy on the operational performance measures like regularity of motion, commercial velocity and effective line capacity within same infrastructure and headway conditions.

To simulate realistic operation behaviour, a dual-train scenario of a leading and a trailing train was adopted. The simulation model combined the longitudinal vehicle dynamics and braking curve calculations, movement authority logic and theoretical driver behavioural model. The architecture was extended one more step to hardware-in-the-loop validation on an Raspberry Pi® platform to explore real-time execution limitations and distributed communication robustness.

The findings indicate that despite the fact that theoretical line capacity in terms of nominal departure headway is the same, signalling paradigm has a major influence on the efficiency of the operation. Moving block signalling also decreased effective headway during terminal arrival by about 8 per cent and increased commercial velocity by about 8 per cent over Fixed block operation. The regularity of motion of trailing train improved by about 0.70 to 0.74 that is, a smoother operational behaviour and minor stationary time within the effective operating period. All these were done without raising the maximum permitted speed, which proves the performance gains are due to optimization of dynamic separation instead of modification of the infrastructure.

The analysis also shows that Fixed block systems have a conservative spacing through the segmentation of infrastructure in discrete blocks (as opposed to Moving block systems which dynamically control the separation through the performance of braking and real-time positioning). This is the physics-based to infrastructure-based separation that is the essence of the efficiency mechanism of better operational fluidity and capacity potential.

A number of difficulties were met in the implementation especially on real-time synchronization, solver configurations, UDP communications stability, and limitations of hardware integration. These restrictions are evidence of the complexity that distributed railway control simulation is by nature, and point to the significance of deterministic execution environment in ensuring that the environment is as industry-grade as possible.

Even though the elaborated framework effectively illustrates the performance gaps in a model of a controlled corridor, further studies should be conducted on the analysis of actual railway corridors like the Milano-Bologna high-speed corridor. The operationally dense conditions would permit testing the benefits of dynamic separation by including real infrastructure geometry, heterogeneity of traffic and variability in timetables. Also, further integration with industrial real-time platforms or FPGA-based acceleration might also improve determinism and scalability.

Conclusively, this thesis proves the presence of quantifiable enhancements of the regularity of motion, commercial velocity and efficient line use in the case of Moving block signalling compared to Fixed block systems with equal nominal limitations. The designed simulation architecture provides a scalable platform on which future research, application on a corridor level, and eventual shift to complex railway traffic management strategies can be installed.

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10 List of figures

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