

Optimisation of Rail-road Level Crossing Closing Time in a Heterogenous Railway Traffic: Towards Safety Improvement

South African Case Study



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Dedicated to

my mother

Sekgabo Flora Tshaai

and

my late father

Keletlhokile Daniel Tshaai

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Abstract

The gravitation towards mobility-as-a service in railway transportation system can be achieved at low cost and effort using shared railway network. However, the problem with shared networks is the presence of the level crossings where railway and road traffic intersects. Thus, long waiting time is expected at the level crossings due to the increase in traffic volume and heterogeneity. Furthermore, safety and capacity can be severely compromised by long level crossing closing time. The emphasis of this study is to optimise the rail-road level crossing closing time in order to achieve improved safety and capacity in a heterogeneous railway network. It is imperative to note that rail-road level crossing system assumes the socio-technical and safety critical duality which often impedes improvement efforts. Therefore, thorough understanding of the factors with highest influence on the level crossing closing time is required. Henceforth, data analysis has been conducted on eight active rail-road level crossings found on the southern corridor of the Western Cape metro rail. The spatial, temporal and behavioural analysis was conducted to extract features with influence on the level crossing closing time. Convex optimisation with the objective to minimise the level crossing closing time is formulated taking into account identified features. Moreover, the objective function is constrained by the train's traction characteristics along the constituent segments of the rail-road level crossing, speed restriction and headway time. The results show that developed solution guarantees at most 53.2% and 62.46% reduction in the level crossing closing time for the zero and nonzero dwell time, respectively. Moreover, the correctness of the presented solution has been validated based on the time lost at the level crossing and railway traffic capacity consumption. Thus, presented solution has been proven to achieve at most 50% recovery of the time lost per train trip and at least 15% improvement in capacity under normal conditions. Additionally, 27% capacity improvement is achievable at peak times and can increase depending on the severity of the headway constraints. However, convex optimisation of the level crossing closing time still fall short in level crossing with nonzero dwell time due to the approximation of dwell time based on the anticipated rather than actual value.

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Chapter 1

Introduction

”In science, when human behaviour enters the equation, things go nonlinear. That is why Physics is easy and Sociology is hard.” **Neil deGrasse Tyson**

1.1 Problem Statement

Rail-road level crossing is a point of shared responsibility between the railway and road traffic. However, there is a high risk of train-vehicle or train-person collisions at these interfaces. In South Africa, there are over 9000 authorised rail-road level crossings [13]. Rail-road level crossings are safety critical in addition to their socio-technical characterisation. As a consequence, there is gradual development on the level crossing safety and capacity improvements due to the dual characterisation. The rail-road level crossing involves a considerable number of human elements. Therefore, safety at level crossings not only depends on technology but also on the human behaviour. Although, automation remains the most viable solution thorough understanding human and technology is essential.

There are two forms of rail-road level crossings, passive and active. Passive rail-road level crossings are equipped with the stationary warning signs as means of protection. Studies have indicated that frequency of incidents at active rail-road level crossing far exceeds that at passive rail-road level crossing [12, 15]. This has led to an increasing reluctance in upgrading passive to active rail-road level crossings. However, in some cases stationary warning signs are not adequate to provide the necessary protection. On the other hand,

active rail-road level crossings employ flashing lights and barriers to warn road users of the approaching trains. At both forms of rail-road level crossings, trains are given first preference because of the railway operational requirements. In addition, speed restrictions are imposed for the railway traffic.

Furthermore, there are no specific rail traffic operations at passive rail-road level crossings this leaves road users responsible for their safety. Conversely, active rail-road level crossings use two points of interests in controlling the protection mechanisms namely activation and deactivation points. Activation point triggers the deployment of the level crossing's warning and protection system. Similarly, deactivation point signals the withdrawal of the warning and protection. Thus, system which is responsible for safe train movements uses track occupancy supervision to trigger and withdraw the level crossing's protection system. Hence, operation of active rail-road level crossings depends on the train detection system.

It is becoming increasingly difficult to meet high level of performance and safety in the midst of the challenges facing the rail-road level crossing system. Thus, trade-off is made between safety and performance. The trade-off often falls short when the user specification is not well defined. In South Africa, railway transportation assumes most of the responsibility concerning the rail-road level crossing. The dire consequence of the unequal responsibility on the management of rail-road level crossings hinders the achievement of a true user requirement specification. However, joint optimisation of technology and human element is essential on socio-technical systems such as level crossings. Thus, without true user requirement specifications, improvement efforts seem futile. The status quo of the management of rail-road level crossings may have been successful in the past but it is no longer sustainable. Particularly, looking at the rate of evolution of the transportation systems involved.

The failure of current rail-road level crossing systems to cater for the ongoing changes in both rail and road transportation is evident. Moreover, safety at the rail-road level crossing cannot be the end user's responsibility. The rail and road transportation have different functional and operational characteristics. In addition, modern trains and vehicles have gotten lighter, faster and quieter over the years. On the other hand, human reaction time is severely influenced by the high ambient noise levels in urban areas. The increased population growth in urban areas implies an increase in transportation demands. Therefore, long rail-road level crossing closing time is inevitable especially

with an increase in traffic volume and heterogeneity.

Studies have shown that accidents at the level crossing follow different trend from the normal road accidents. Thus, accidents at rail-road level crossing are mostly caused by unintended or intended human error as opposed to excessive speeding or driving under the intoxicated substances [12, 28]. Hence, a summary of human errors with high likelihood of causing an accident at the rail-road level crossings are as follows.

- Belief and assumed knowledge of the road transport network, train movement and the operation of the level crossing [15]. This can further be broken down into the following
 1. Blindness caused by the lack of attention which leads to failure to perceive an object in plain sight [12].
 2. Perceptual limitation resulting from the interference in human vision caused by the sun glare [15].
 3. Expectation – in most cases human beings are guided by their expectations rather than the environmental stimuli. Thus, expectations that there will be no train approaching the level crossing is evident in the increased likelihood of failure to respond to level crossing protection mechanisms [12, 15].
 4. Speed or distance perceptions - passing through the level crossing requires accurate decisions with respect to the train's speed and distance. This is a complex perceptual process of the relative speed and distance of two objects that are converging at different speeds and often at angles that are not always perpendicular [15]. Hence, this decision-making process is highly vulnerable to error [12, 15].
- Late detection of warning as a result of lapses and errors impeding decision making process [10, 20]. Motorists and pedestrians can experience a delay in interpreting warning of the approaching train late especially when barriers are excluded in the level crossing protection system.

1.2 Research Rationale

It is evident that advanced technological solutions deployed at the rail-road level crossing maybe impeded by uncontrollable human behaviour. Yet, the consequences of accidents

at such systems include severe injuries or fatalities and damage to expensive rail assets such as train and track-side equipment. Moreover, collisions at the rail-road crossing can also result in the railway service disruption and traffic congestion. Thus, safety at the rail-road level crossing relies on both technological advancement and appropriate human behaviour in accordance with defined standards and traffic rules. However, level crossing technical and human behavioural analysis do not always align.

Often, level crossing system's safety is compromised by abnormal and degraded modes of operation. Degraded mode of operation is the system's failure to meet the level of services expected by the operators due to intermittent or concurrent breakdowns. The persistence of degraded mode over a long period of time results in the system defaulting to emergency. Furthermore, system may operate under abnormal mode because of unfavourable conditions such as severe weather conditions and increased traffic flow. Thus, it is clear that efficient capacity utilisation of the railway network can be easily achieved for homogeneous traffic as opposed to heterogeneous traffic.

On the other hand, railway infrastructure is costly to build and to maintain. Therefore, shared railway networks are more sustainable than multiple networks catering for specific homogeneous traffic. Shared railway network accommodates heterogeneous traffic such as commuter, intercity and freight trains. However, heterogeneous railway track is most likely to increase the rail-road level crossing closing time and deteriorate system's performance. In addition, fixed level crossing activation point will result in constrained capacity of the railway infrastructure and traffic flow. Hence, this research addresses the rail-road level crossing closing time in a shared railway network. The research hypothesizes that optimal rail-road level crossing closing time in a heterogeneous railway traffic can be achieved by joint optimisation of technical and human element. In addition, direct dependency between technical and human elements need to be established in order to achieve optimal level crossing closing time.

1.2.1 Research Objectives

The main objective of the study is to provide an optimisation solution to minimise rail-road level crossing closing time such that it improves capacity and safety. The proposed solution is intended for railway networks with heterogeneous traffic. Nonetheless, the solution should still apply in a homogeneous railway traffic. Hence, the main objective

of the study is fulfilled in the following steps:

1. Analysis of the level crossing's spatial, temporal and behavioural elements.
2. Extraction and assessment of features influencing level crossing closing time.
3. Implementation of a convex optimisation solution based on the findings of the above mentioned steps.
4. Comparison of the proposed solution to the existing solutions.

1.2.2 Research Outcomes

The present study aims to address the improvement of safety and capacity of the rail-road level crossing through optimisation of the closing time. This shall be accomplished by conducting spatial, temporal and behavioural analysis to identify factors contributing to long waiting time at the level crossing. Thus, the objective is to minimise the level crossing closing time taking into account the features extracted from data analysis and the traffic heterogeneity. The conditions favouring the minimal closing time are formulated as the constraints of the optimisation solution. Hence, this research is set to reduce time lost at the level crossings by at least 50% for both heterogeneous and homogeneous railway traffic. Furthermore, the logical correctness of the proposed solution shall be validated as per CENELEC standards [14, 16, 17].

1.2.3 Scope and Limitations

The present study is limited to active rail-road level crossings in South Africa particularly those in urban or metropolitan areas where there is an increase in rail and road traffic. In addition, it is intended for heterogeneous railway traffic but it is still applicable to homogeneous railway traffic. Data analysis shall be conducted on data collected from homogeneous railway traffic due to unavailability of data at heterogeneous railway traffic. Thus, necessary adaptation shall be applied to ensure that the proposed solution caters for heterogeneous railway traffic. The solution shall not cover degraded mode of operation. Lastly, only a limited train traction and braking characteristics shall be considered.

1.3 Thesis Overview

A brief outline of the thesis is given below:

1. **Chapter 2** covers related works in rail-road level crossing system. Thus, existing literature is broken down into sections covering operations, control, validation and verification. The section on operations puts forth the constituent modules involved in the level crossing operation. Furthermore, the section discusses applicable train detection methods, their advantages and short falls. The role of train detection in rail-road level crossing operation is also elaborated. In addition, the section discusses the purpose and types of the protection system at the rail-road level crossing. The section covering level crossing control outlines applicable level crossing control strategies however an emphasis is on petri nets. The chapter concludes with a brief overview of validation and verification methods applicable to the level crossing system.

2. **Chapter 3** details data analysis of rail-road level crossings located along the southern corridor of the Western Cape metro rail. Data analysis is focused on the extraction of spatial, temporal and behavioural patterns of the rail-road level crossings under study. The chapter further illustrates how spatial, temporal and user behavioural features impact safety at the rail-road level crossings. Thus, spatial analysis presents road and rail based spatial features and assess of their impact on the level crossing closing time. Hence, road-based spatial factors considered include pavement condition, intersection angle, level crossing area and the visibility of the events at the level crossing from the perspective of the road user. Similarly, rail-based spatial factors include the presence of platform, rail profile, rail curvature and length of island track/s. In addition, temporal analysis focuses on identifying and assessing factors contributing to long closing time. At last, behavioural analysis explore unsafe behavioural conducts of each respective users of the level crossing and the factors contributing such behaviour.

3. **Chapter 4** outlines the formulation of the proposed solution and results. The first section of the chapter presents an overview of convex optimisation followed by the formulation of the problem model. Optimal level crossing closing time is critical in ensuring improved capacity and traffic control. Moreover, optimal level crossing closing time has the ability to improve safety. The presented solution involves the application of convex optimisation to minimise the impact of features influencing

rail-road level crossing closure duration using "cvx" solver in Matlab. Constraints due to traction and braking characteristics of different train types and station's dwell time are taken into account. Furthermore, the solution is constrained by the required headway time, safest minimum and maximum level crossing closing time. Thus, two solution architectures for rail-road level crossings with zero and non-zero dwell time are presented.

4. **Chapter 5** presents validation and verification methods applied to check the correctness of the proposed solution. Thus, demonstrating how the proposed solution achieves improved safety and capacity. Any railway system or solution must be subjected to rigorous validation and verification processes the same is applied to the developed solution. The CENELEC standards such EN 50126, EN 50128 and EN 50129 are the most applicable. However, due to time constraints only temporal specifications concerning safety and capacity of the level crossing are checked. The time lost at the level crossing is used to measure safety improvement. In addition, capacity improvement is measured by the headway time and capacity consumption.

Chapter 2

Literature Review

This chapter discusses related works in rail-road level crossing control, operation and validation. It further reviews efforts made towards safety improvement at the rail-road crossings. The chapter is organised as follows, introduction is given in section 2.1. Operational requirements and methods of the rail-road level crossings is presented in section 2.2, followed by the applicable control strategies in section 2.3. Applicable validation and verification techniques are presented in section 2.4 followed by concluding remarks in section 2.5.

2.1 Introduction

Railway signalling systems has an average life cycle of at least 20 years. However, the rail-road level crossing system reaches saturation level within the first half of the stipulated time. This results in the deterring system's safety and performance. The railway traffic shares the rail-road level crossing infrastructure with other modes of transport. Moreover, continuous increase in transportation demands and evolution of the rail and road vehicles is expected within the stipulated life cycle duration. Therefore, the increase in failure to respond to warnings of the approaching train is no surprise. As a result, the level crossing safety deteriorate thus the lives of other users is put in danger.

The rail-road level crossings have been found to increase the train's travel time in the network. In addition, rail-road level crossing accidents are the third contributor to fatalities in the South African railway network [13]. This has led to the call for improveme-

nts of safety at the rail-road level crossing. However, the socio-technical and safety critical duality of the rail-road level crossing system often impedes improvement efforts. Therefore, the shortfall comes from trading the system performance for achieving the required safety integrity level [34]. This approach may show great success at the beginning but it is not sustainable. Extensive literature on the improvement of safety at the rail-road level crossing systems exists. Hence, the review of the existing literature shall be categorised into the operation, control, validation and verification of the rail-road level crossings.

2.2 Operation strategies

Railway train control system is the backbone of safe and secure operations of the trains [51]. Thus, rail-road level crossings have separate operation strategy which feeds into train control system. Intelligent control is critical in ensuring unified feedback between the train control and level crossing systems [47]. Therefore, development of automatic train control systems is at the forefront of providing safe train operation and overcoming the challenges faced by the railway industry [19, 51]. Automated systems in railway are facilitated by railway traffic management system based on the adopted operational methods, such as fixed and moving block signalling systems [52]. The fundamental principle of railway signalling systems is to maintain a safe distance between successive trains travelling in the same or opposite direction [49, 52]. The safest distance is established by the signals used to guide the trains or train localisation information available through cloud computing [35].

While there is growing interest in automated train operation, there is a gradual development in the optimisation of the rail-road level crossing operation. The study of rail-road level crossing is intricate because it involves at least two modes of transports with different operation and management. Furthermore, the rail-road level crossing system is safety critical and socio-technical [7, 11]. The presence of the rail-road level crossings in the network has been shown to increase the train travel time which impacts the capacity of the network [8, 34]. In most cases the time delay caused by rail-road level crossing are not assessed on day to day case, but only during design phase or in the event of an accident. Rail-road level crossing controllers derive their inputs from the activation track circuits to enable protection systems such as the siren, lights and barrier [8]. Therefore, rail-road level crossing closing time is dependent on the train detection, control and protection systems [31, 33].

Train detection is achieved by application of various technologies such as track circuits, transponders and odometric sensors explained in subsection 2.2.1. In addition, the applicable level crossing control strategies and protection systems are outline in 2.3 and 2.2.2, respectively. It is often assumed that the train travel at the maximum allowed speed on the approach or over the rail-road level crossings however it is not always the case. The controller uses the train occupancy status of the activation track to warn and protect the level crossing irrespective of the speed of travel of the approaching train. Hence, long rail-road level crossing closing time is expected in the case where the train are delayed upon occupying the activation track [8, 33]. Nikolajevs et al. proposed the measurement of the train's entry speed through the evaluation of the changes in inductance and impedance of the track circuit [33]. Further, the rail-road level crossing closing time can be inferred from the changes in inductance and impedance [8, 33].

The level crossing protection system is triggered as soon as the train is detected on the activation track monitored by the block occupancy circuits [8, 31, 33]. The study conducted by Nikolajevs et al found that the long closing time is attributed to the train travelling at the speed significantly lower than the maximum permissible speed. Hence, this is a result of activation being triggered at the same point for the train travelling at maximum permissible speed and that travelling at significantly lower than the maximum permissible speed [33, 34]. Thus, the first case will results in the lower closing time than the latter [33]. The study proposed prediction of the rail-road level crossing closure duration based on the train speed measurement either by additional sensors or evaluation of track circuits impedance [33]. However, approach of additional sensing is often not preferable due to cost of installation and equipment.

Several attempts have been done to reduce the rail-road level crossing closing time without the need of additional equipment. Nogushi et al proposed the reduction of the level crossing closing time using optimal rail-road schedule. Thus, optimal schedule was calculated using a genetic algorithm such that time delay for each train at a station is the gene value and the blocking time is the fitness value [74]. Hence, the applied genetic algorithm of 30 individuals and 1000 generations generated the combinations on the train's departure time which reduces the level crossing closing time [74]. The study confirmed that closing time reduced for changing combinations of the departure time [74]. In addition, Alps et al developed a control algorithm for the rail traffic routes with predefined schedule over the rail-road level crossing. The proposed solution showed that

the rail-road waiting time can be reduced through the application of the genetic algorithm on the calculation of the schedule taking into account the train's location and speed [75]. Furthermore, the algorithm achieved an increase in traffic capacity at the rail-road level crossing [75].

The secondary challenge with rail-road level crossings is managing and controlling traffic bottlenecks in their presence. The impact of rail-road level crossing system on the railway planning and operation is often significant and if not monitored may result in adverse consequences [7, 22]. Planning and operating railway is a difficult challenge because of the general complexity of the underlying discrete optimisation problem [50]. The process of train timetabling involves minimising of process time. Thus, one need to consider the section run-time, dwell time and headway time in the optimisation process. In addition, train timetabling process must be satisfied to ensure feasibility and the scheduling of trains to meet the passenger demand [23, 31, 50]. However, train timetable became difficult to solve due to an increase in passenger demand and heterogeneity of train service as well as geographical conditions [36, 50]. The increase in customer demand for railway transportation services often results in oversaturated railway systems and consequently leads to traffic bottlenecks [36]. Remedial actions can be applied to railway traffic but it fails in increasing capacity distributions at the interface with other modes of transportation. Timetable planning with heterogeneous railway traffic is a complex task because of the different operational train properties [32, 37].

2.2.1 Train Detection

Train detection plays a critical role in the operation of the rail-road level crossings. Hence, the level crossing controller input is derived from the track occupancy status defined by the train detection system. Thus, train detection over the activation track serves as the input on the controller which then actuates the level crossing protection. Similarly, as the train clears the deactivation track the controller responds by withdrawing the protection. The emphasis of this section shall be on train detection technologies other than the axle counter. Thus, axle counter based train detection shall be discussed in section 3.1.2. Furthermore, these technologies are categorised into analog, digital and intelligent subtypes.

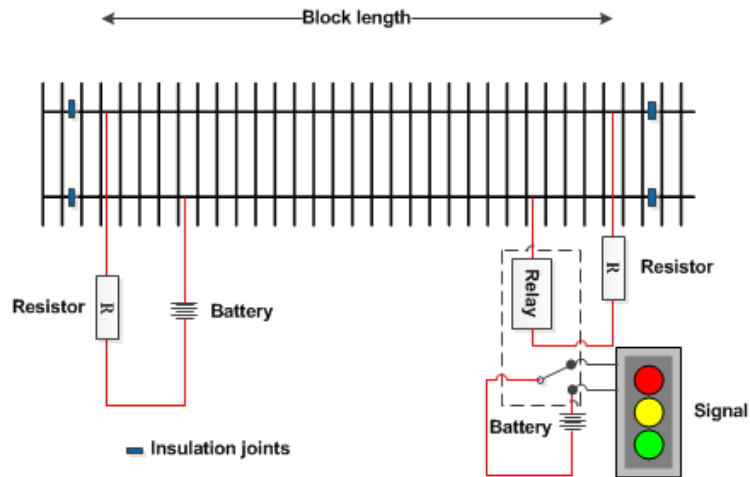


Figure 2.1: DC track circuit

Analog Train Detection

Traditional train detection involves direct current (DC) or alternating current (AC) track circuits. In both methods, the railway line is divided into segments of varying length called blocks. The blocks are co-joined by insulation joints in order to enable continuous train detection as it transverse along the railway line. However, the required insulation joints material is expensive to install and maintain [56]. Furthermore, insulation material is prone to deterioration [56]. The train detection by DC track circuits is based on the propagation of an electrical signal along the two rails, as shown in Figure 2.1. A resistor in series with the DC source limits the current flow when the train is detected. Hence, DC signal source is connected to the both rails on one side of the block and the relay acts as receiver connected to the other side of the block, as depicted in Figure 2.1.

When the track circuit is unoccupied, the DC supplied by the source on one end of the block will run along the rails and energise the relay located on the other end. However, when the track circuit is occupied, the train axles connect the running rails together resulting in a short circuit. This reduces the current through the relay and de-energises it. Thus, track circuit can have any of the three statuses faulty, occupied and free. These statuses are inferred from the comparison of the current measured on the receiving end and the threshold current value. The set threshold current takes into account the detection criteria and the losses under given operational condition.

DC track circuits are ideally applied on a non-electrified railway sections due to their susceptibility to stray currents [56]. In addition, double-rail DC track circuits suffer

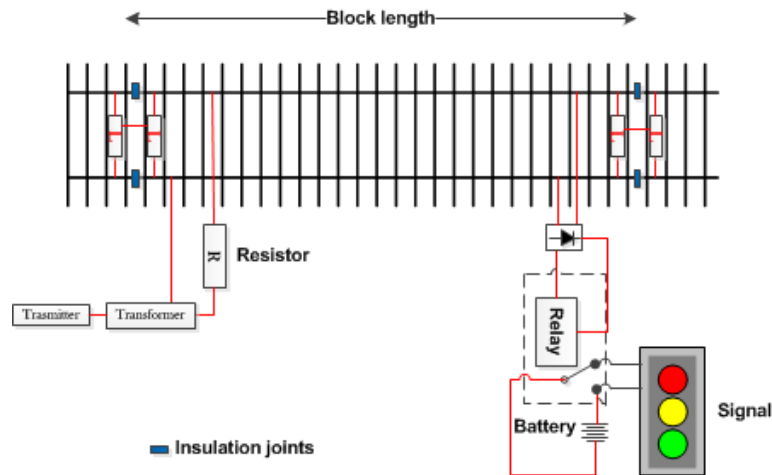


Figure 2.2: AC track circuit

from the interference due to propulsion current generated and returned from the rails. As a result, distance from the signalling point is limited by the leakage current flowing through the ballast. The leakage current is generated by the attenuation of the applied voltage between the rails [56]. Ballast is the rail bed on which sleepers (concrete/metal blocks underneath the rail tracks) rest on. The second shortfall of DC track circuits is the use of the fixed threshold for joint optimisation for train detection, broken rail and communication breakdown [56].

AC track circuit technology was introduced to counteract the DC track circuit's susceptibility to stray currents from the traction system. This requires the use of AC signal source operating at frequencies above 60Hz such that interference from the 50Hz traction current is avoided [55]. AC track circuit has an additional pair of impedance bonds for each pair of the insulation joints, shown in Figure 2.2. The impedance bond comprises of the centre-tapped inductance connected across the rails on both sides of the insulation joints [55]. This provides continuity between the track circuits for the DC propulsion power and propulsion current distribution. In addition, impedance bonds will maintain relatively high impedance at the signalling frequencies between the two rails and adjacent track circuits. Thus, AC signal transmitted propagates along the rails will energise the relay at the other end of the track circuits when the track circuit is unoccupied. Similarly, the detection of the train's axles will result in the reduction of the current through the relay thus de-energise it.

It is expensive to maintain insulation joints associated with AC track circuits. Thus, the need for the insulation joints was eliminated by the introduction of high frequency alternating current (HFAC) track circuits. In a HFAC track circuit, the edges of the block

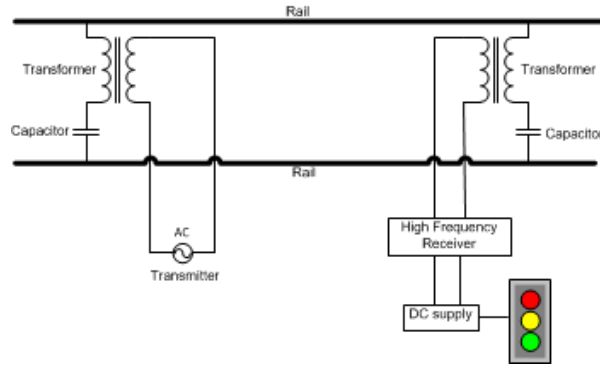


Figure 2.3: HFAC track circuit

are established by a special transformers connected to the rails as indicated in Figure 2.3. These specialised transformers have single turn winding made of heavy copper bar stork and a toroid core [55, 56]. Hence, transformer on the transmitter side operates at the frequency of the transmitted signal whereas that on the receiving end operates at the frequency of the receiver circuits. The receiver is an electronic circuit consisting of the tuned filter, rectifier and amplifier to receiving the transmitted signal.

Train detection in an HFAC track circuit is established by either de-tuning the receiver circuit or short-circuiting the transmitter or receiver or both. However, transmitted signal is used to keep the track energised when the track circuit is unoccupied. HFAC track circuit requires assembly of single transformer between adjacent track circuits. The resonant windings for the track circuit and adjacent track need to be isolated as they operate at different frequencies. Furthermore, isolation of the resonant windings require blocks to be at least 800m long which is impractical for inner city railway network [56].

Henceforth, modulated signal with high spectral density was proposed to address the HFAC track circuits limitations of isolating resonant windings [56]. This led to the introduction of passive signalling devices (PSD) in train detection. Thus, PSD is a switch which senses the current through the detection point when closed and has an opposite effect when opened. The modulated signal includes pulse amplitude modulation (PAM), orthogonal frequency division modulation (OFDM) and quadrature amplitude modulation (QAM). A unique operating sequence is used for each detection point through the application of a assigned duty cycle for occupied block, free block, broken rail and communication breakdown functions [55, 56]. Communication between the adjacent detection points is established by PSD modulating voltage or current from the neighbouring detection points [56]. Therefore, the application of the modulated transmit signal in track circuit ensures optimisation of all functionalities of the track.

Intelligent Train Detection

Intelligent train detection is the future and this is mostly accomplished by odometry and binary coded track circuits. Odometry is the method of determining the position or location of the train from the velocity and acceleration sensors mounted on the rail or the train. Moreover, accurate train localisation by odometric system requires multi-modal sensor network [61]. Therefore, odometric evaluation methods are compatible with automation due to its reliance on the use multi-modal sensors in addition to guaranteed safe, reliable and available services. Most of the applicable sensors include radar, cameras, inertial navigation system (INS), radio frequency identification (RFID) and tachometer. Thus, odometric evaluation requires large data acquisition and processing.

Large amount of data is required at a low acquisition rate defined by the analog to digital converter (ADC). The application of ADC allows for maximum resource utilisation and general purpose data acquisition [44]. Hence, different techniques such as direct ADC and frequency to voltage converter based methods are applicable in data acquisition. To make reference, the application of the wheel angular sensor in odometry involves the computation of the wheel speed from numerical differentiation of the impulse counters. In addition, wheel acceleration is estimated by subjecting the computed wheel speed values to filtering [61]. As a result, voltage amplitude is proportional to the input frequency whilst the frequency of the angular speed is proportional to the angular speed. Angular speed signal is treated as an analog signal thus processing technique extract angular speed from a logged data using direct ADC method [44]. Similarly, frequency to voltage method converts the frequency of an angular speed signal into a voltage signal using frequency to voltage circuitry [44]. However, the conversion method is inherently slow due to applied averaging processes and inadequate capturing of the transient response [44].

State variable evaluation is the common system identification method applied in odometric sensors. Thus, state variable evaluation involves identification of the current state of the system and appropriate application algorithm [61]. This implies that a sensor in a fail state cannot be used for estimation of the measurable. Hence, reckoning can be applied in case of limitations in number of sensors, their configuration and operating environmental conditions [38]. However, addition evaluation criteria must be applied. Tachometric is one of the common evaluation criteria. It stipulates that the train's wheels are in slid or skid mode if the absolute value of the difference between the peripheral speed of the wheels exceed the defined threshold value [61].

In accordance with accelerometric criterion, train wheels are sliding if the absolute difference between the estimated and measured acceleration exceed a fixed threshold [61]. Thus, slid mode is evaluated based on the comparison between the estimated and measured wheel acceleration [44]. In addition, conditions such as the rail curvature, wet tracks, fast acceleration and deceleration have been identified to have high slip or sliding effects [46, 43]. Thus, slip or slide counteracts measures such as fuzzy logic and neural network based anti-slipping control were proposed [46, 38]. Neural network based anti-slip control is success when applied in estimation of the friction between the rail vehicle's wheel and the rail tracks [46]. Whilst, applicable fuzzy logic anti- slipping control methods include re-adhesion algorithm nested with creep control and oscillation suppression control are effective with the use of non-contact speed sensors such as radar, RFID and navigation systems [46].

The primary objective of odometric evaluation is to provide train position, speed and acceleration. Thus, train localisation is essential element of these measurements. Accelerometer, angular speed, radar, navigational systems and optical sensors are amongst sensors used in train localisation. To make reference, train's longitudinal acceleration can be used in odometric evaluation to derive the train's position and speed by numerical integration. This is achieved by accelerometer with low bandwidth so that it can be able to measure train's longitudinal acceleration with high sensitivity [44]. However, vertical component of the acceleration will be measured since axle accelerometer is not perfectly horizontal. This results in angular misalignment with respect to the horizontal axis. Moreover, the angular misalignment is perpendicular to the sensitive direction of the longitudinal acceleration measurement [61].

In order to increase the accuracy of the odometric estimation in critical adhesion conditions, inertial mass units (IMU) are the best approach [38, 39]. IMU measures the three-axial body frame acceleration and the three-axial body frame angular rate using its three-axial accelerometer and a three-axial gyroscope [38]. This is to compensate for the accelerometer's sensitivity to gravity and centrifugal force [38]. Although IMUs gives accurate measurements, they are also limited by the cost of acquisition and maintenance. Therefore, reliability of the odometric estimation is dependent on the set of sensors used and the required operative conditions [38, 39]. Conventional odometry algorithms have proven to be sensitive against wheel-rail adhesion conditions and may fail in the presence of high sliding [38].

Thus, degraded adhesion conditions are critical for these algorithms. The performances of wheel speed sensor-based odometry algorithms are influenced by the shape of the measured wheel speed profiles at low adhesion coefficient [38]. However, wheel angular speed sensors are highly reliable against slide and skid [46, 42, 40]. The wheel angular speed sensor measures the peripheral speed of the train. Thus, precision of the odometric speed estimation is dependent on the information of the wheel diameter (R) under the non-sliding condition [42, 46]. Similarly, a combination of two angular speed sensors can be used to determine and compensate the errors due to the wheel diameter as the wheels are subjected to wear and tear [42]. Degraded wheel-rail adhesion (sliding) condition corresponds to the train accelerating when the peripheral speed exceeds train speed. Likewise, the train is braking when the train speed exceed peripheral speed [40].

Tachometers are relatively new in odometric train localisation. They are available in capacitive, active and passive electromagnetic form however recent development are focused towards optical form which less susceptible than the others [40]. Tachometers are used in train position and velocity measurements. However, they are prone to errors due to wheel slip and slide [42, 43]. Furthermore, they have high likelihood of resulting in non-detection of the trains [40]. The only way to minimise failure modes is to increase the number of sensors which is not always practical [40]. Alternatively, radar sensors can measure the relative speed between the body they are mounted on and the surface to which they are pointing to. The speed measurement is achieved by detecting the frequency shift between the transmitted and the received echo reflected from object of interests [46]. The advantage with radar sensors in odometric train detection is due to being less susceptible to weather conditions and the time of the day. However, the problem with radar is its dependency on Doppler shift which results in the variability and uncertainty in the received signal from the rail track [46].

Conversely, high speed railway networks use satellite based navigation systems for train localisation and speed measurements. These include the application of Global Positioning System (GPS) which is similar to tachometer but have high precision and cost of acquisition. At least four satellites are required for accurate target positioning within 5m-20m. Additionally, error correction is required for ionospheric and tropospheric delays [42]. The major shortfall with satellite based navigation system such as global position system (GPS) is the outage of the GPS signals in tunnels and urban canyons [42]. The proposition of inertial navigation system (INS) originated from addressing GPS signal outage. Thus,

INS measures the changes in position, velocity and altitude of the train as it transverse along the rail tracks [42]. However, this approach is limited by the susceptibility to errors and size of the sensors.

Last but not least, optical photoelectric devices are used to measure train's speed in-situ. This include camera which can directly identify and distinguish between the different point machines and [48]. In application of camera, odometric method evaluates train speed based on the movie frame count at-grade track or where landscape permits [46, 48]. Although, camera can contribute to accurate track selection it is less desirable for real-time application since a fixed reference points on the video must be defined in order to achieve precise measurements [48]. Alternatively, radio frequency identification (RFID) can be applied. RFID determines the position of the train by the tags and reader. At close proximity, the tag transmits signal and its identity to the reader which receives the signal and identifies the tag [42]. However, large amount of RFID sensors are required for accurate train speed and position measurement [42].

Digital Train Detection

Most railway signalling systems with automatic train protection (ATP) make use of coded and binary coded track circuits. The coded track signal is sensed by a pair of coils mounted underneath the train before the first set of axles. The sensing coils are referred to as antennas. Magnetic field generated from the current running on the rails, induces signal on the antennas [55]. Hence, this approach is compatible with DC or AC track circuits. Moreover, signal on the track circuit is switched on and off at a rate at which the speed command is received and interpreted by the on-board system [55].

In the application of coded track circuit with DC track circuit, transmitted direct current running on the rails is modulated at desired rate on the other end of the block [55]. Hence, wayside signalling elements on the receiving end will receive and decode track occupation information. Similarly, in the application of AC track circuit switching rate is slower than the frequencies of the transmitted AC signals. Therefore, many cycles of the AC signal occur during the time interval that the code is switched on [55]. The relay is energised when the code is received and this information is then used to control trackside signalling equipment. The detection of the presence of the train will seize the operation of a relay responding to the code. As a result, occupation of the block gets established.

In contrast, binary coded track circuit work in conjunction with the high frequency track circuit. The frequency of the track section is toggled between discrete frequency values [55]. Thus, generated signal is referred to as binary frequency shift keying (FSK) modulated signal. The FSK signal is then adapted to digital systems in which one frequency is classified as a mark frequency corresponding to transmission of a "1" and the other classified as space frequency transmitting "0" [55]. Therefore, train detection is established when the amplitude of the signals at the receiver is reduced below the threshold. The FSK modulation technique is trivial in digital signal processing due to its immunity to noise from constant envelope [55, 60]. In addition, it has low probability of error and high signal to noise ratio (SNR). Other frequency shift keying modulations can be applied in the case where more than two discrete frequency values are required. The modulation techniques referred to are quadrature frequency shift keying (QFSK) modulation and M-array orthogonal frequency shift keying (MFSK).

2.2.2 Protection Systems

The rail-road level crossing protection system provides warning of the approach of the train and secures the level crossing on the passage of the train. Moreover, the protection system is distributes traffic capacity amongst the involved modes of transport. Barriers, light, sound and object detection method can be used to protect level crossings. Although, the protection system can make used at least one of the methods, multi-modal protection system is most preferred. Multi-modal protection systems improve responsiveness to the warnings [9, 15]. However, intelligent systems require additional object detection technologies in the protection system [3]. Rail-road level crossings are characterised as socio-technical systems due to the interaction of human element and technology in operation. Therefore, it is important that level crossing protection reinforce safety amidst technological limitatio-ns, human factor and spatial constraints.

Rail-road level crossing protection cannot be dealt without an understanding human element. However, human element is complex and therefore difficult to successfully assess. Amit et al argued that impact of human element at the rail and road interfaces can be categorised into anatomical, personal, psychological and social attributes [15]. Anatomical attributes relates to age, fatigue level, cognitive, auditory abilities of an individual user. Yet, personal attributes concerns the attitudes of individual users towards the rules and others users of the rail-road level crossing. Psychological attributes emanates from the stress and assumed knowledge of the operation of the level crossing system.

Likewise, social attributes are as a result of crimes and conflicts effects on the individual. Risk and accident analysis indicate that human factor impact is difficult to map its causations accurately. Salmon et al presented a study on the dependencies between the systemic and psychological factors in compromising safety at the level crossings following Kerang crash.

Thus, systemic approach applied in the assessment of the Kerang level crossing crash is based on safety being an emergent property of non-linear interaction between the components of the system [5, 6]. The study argued that systemic safety approach at the level crossing is dependent on the integration of the components of the system which ensures that decisions made at higher governmental, regulatory and managerial level is filtered through to the end-user of the system [6]. Furthermore, the psychological analysis of the Kerang crash was conducted on a schema-based human cognitive and behaviour method. Schema theory propose that individual possess mental templates of past experiences which are mapped with the information in the world to produce behaviour [6]. Therefore, schema allows individuals to orientate towards incoming stimuli and adapt their response to it [6].

The schema based perceptual cycle model indicated that human failure to adhere to the warning is attributed to various factors. Hence, the absence of physical barrier in the protection system, truck driver obscured by the vegetation and truck driver's failure to respond to the sound alert (blown horn) of the approaching train were identified to be critical in the cause of the crash [6]. However, there were also systemic failures identified such a lack of educational awareness, delayed truck loading, inadequate inspection and monitoring of the near-misses at the rail-road level crossing [6]. In addition, an observational field study on motorist's risky behaviours at the rail-road level crossing was conducted in France. Thus, statistical analysis of the motorist's behaviour was performed based on three durations. The time at which initial warning is given, time at which booms start closing and time at which booms are completely closed [54]. The level crossing protection was organised in a way that initial warning comprising of flashing lights and sounding siren until the booms close.

The analysis indicated that motorists tend to intentionally ignore the warning of the approaching train within the first 2s of initial warning and closing of the booms [54]. Moreover, the likelihood of motorists intentionally ignoring warning was reported to be high during daytime [9, 54]. A large sample of data showed that most motorists ignore

warning from flashing lights and siren. However, they are more responsive to the barrier based protection system. Furthermore, the rate of non-compliance is high at peak hours in the morning and evening [54]. The non-compliance observed during the time at which booms are closed included the "zigzag" behaviour in half barrier based warning systems [54]. The study indicated that about 50% of non-compliance occur within the first few seconds after the closure of the barrier [54]. Hence, the study recommended a shorter clearance time for flashing lights and reduced barrier closure time in the event of more than one train crossing [54].

In addition, rail-road level crossings are safety critical thus a loss any functionality can have catastrophic effects. One of the technical factors affecting safety at the level crossing is long waiting time [8, 31, 33]. However, the mode of operation of the level crossing system could have adverse impact on the safety than long closing time [27]. Level crossings systems are susceptible to abnormal, emergency and degraded modes of operation. A level crossing system is said to in abnormal mode when operating under severe weather conditions and increase in traffic volume. Thus, severe weather conditions affects the rail and axle contact of the train and may consequently result in trains travelling slower than normal and hence long waiting time [27, 29]. In addition, an increase in rail traffic volumes may require the level crossing to remain closed for longer in order to allow all the trains to safely pass. Therefore, level crossings with both long closing time and abnormal mode of operation have high safety and capacity risk.

Conversely, degraded mode of operation results from the loss of critical functionalities of the system such as loss of detection or malfunction of the protecting system [29, 30]. Human intervention is required to mitigate degraded mode of operation. Hence, the system defaults to emergency mode of operation when either degraded or abnormal mode persist over a longer period of time [27]. The system's mode of operation may also indirectly contribute to accidents at the level crossing. Furthermore, the co-existence of the degraded or emergency with long closing at the level crossing could result in catastrophic effects [29, 27]. It is therefore critical to consider the human behaviour when designing the level crossing protection system. Moreover, continuous monitoring of the human behaviour is essential the assessment of the effectiveness of the level crossing protection system.

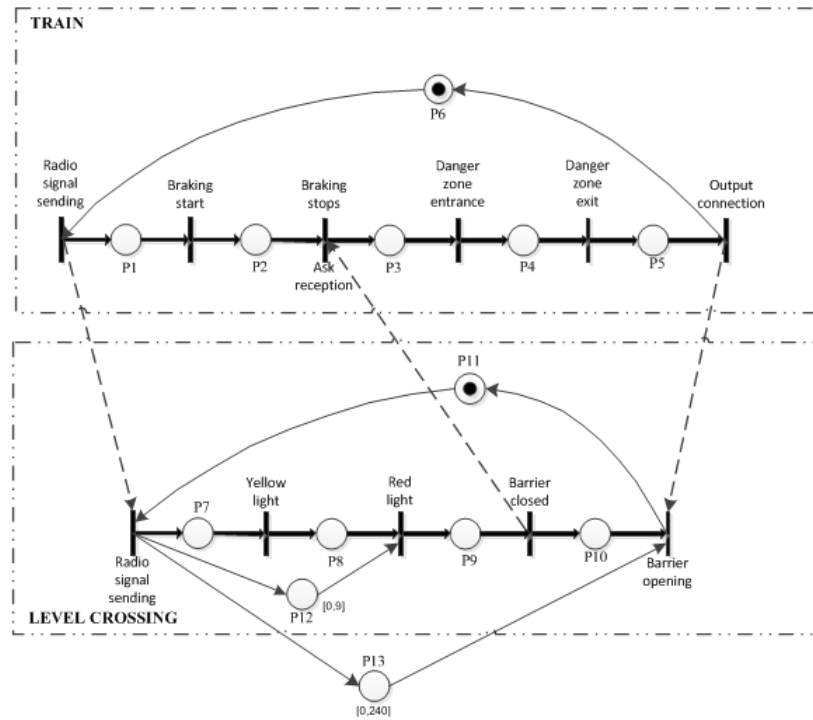


Figure 2.4: The application of petri nets in level crossing control

2.3 Control strategies

The level crossing control facilitates capacity distribution of the railway and road traffic. Thus, various control strategies have been applied at rail-road level crossings. Most of the control strategies applied focus mainly on the safety improvement at the rail and road interfaces. Furthermore, increase reluctance in automation of the rail-road level crossing system is attributed to limited support of new technological changes and unequal responsibility between stakeholders. Railway transportation is faced with numerous challenges such as capacity optimisation, energy conservation, cost reduction and reliability of the services. Therefore, challenges of rail-road level crossings are often neglected due to their urgency relative to other challenges and stakeholder engagement. Applicable rail-road level crossing control strategies are discussed below.

Petri nets (PNs) modelling is the commonly applied control technique in rail-road level systems. PNs are a set of mathematical modelling techniques for analysis of asynchronous, non-deterministic, stochastic, parallel and distributed systems [2, 8, 21]. They can be applied in system identification problems where state and algebraic equations are used to model the system behaviour [18, 21]. However, their application in railway transport ranges from performance evaluation, communication protocol, fault tolerance and human factor assessment. Its variety of extensions such as Coloured Petri nets (CPNs), Timed

Petri nets (TPNs), Stochastic Petri nets (SPNs) and Generic Petri nets (GPNs) makes it strongly competitive over other control techniques. Petri nets contain places (marked by circles) and transitions (indicated by blocks) connected by directed arcs, as shown in Figure 2.4. Thus, places represent states or conditions or resources which need to be met before an action may be taken out. Whilst, transitions symbolises the actions to be taken based on the satisfaction of the states or conditions. Places may contain token (indicated by the solid circle within empty circle) which move to their specified places through execution or "firing" of actions.

In PNs application, time is critical in most since most of the systems are non-causal. Therefore , TPN associate time with places, transitions and arcs. Furthermore, it is preferable to associate time with transitions as it represents activities [62]. This allows for prioritisation of mechanisms whereby multiple transitions compete for the same token and transition with highest priority is executed first [21]. Thus, application of SPNs on the safety of the rail-road level crossing has led to the establishment of the functional and dependability (ProFUND) modelling process [20, 21]. The objective of the ProFUND modelling process was to harmonise different safety standards and establish a cross acceptance benchmark across railway sector [21]. Though ProFUND modelling has shown a great success in dealing with functional dependencies advancement can be made to include human behavioural modelling through the application extended deterministic and stochastic Petri nets [21].

Furthermore, Dutilleu et al. proposed the use of p-time Petri nets (p-time PNs) over the TPNs in modelling and synthesis of the level crossing control system. Petri net model of the train and level crossing processes were developed. The models are illustrated in Figure 2.4. Thus, p-time PNs control begins with the train sending the radio signal to the level crossing. As a result, the train starts to brake whilst waiting for the acknowledgement from the rail-road level crossing system [62]. The acknowledgement is a signal regarding the safety status of the crossing. Thus, the signal is a confirmation that the level crossing's protection system is activated. Therefore, when the train receives acknowledgement from the rail-road level crossing system, it will stop braking and proceed further [62]. Moreover, the train is monitored from the level crossing approach until it safely exits. Once the train has exited the level crossing, the signal is sent to the rail-road level crossing system to release protection mechanisms (lights and barriers). Temporal constraints involving the minimum (denoted by P12 in Figure 2.4) and maximum (denoted by P13 in Figure 2.4) closing time were imposed [2, 62]. The minimum and maximum closing time was set to 9s and 240s, respectively. Henceforth, the level crossing closing procedure is cancelled

should it not exceed 9s with an exception of overlapping movement of trains.

The introduction of geographical information systems (GIS) on the rail-road level crossing control was proposed by Ishak et al. Thus, this feature addressed the gap in current level crossing control mechanisms by incorporating the understanding of incidents and precursors [21, 8]. Hence, GIS feature took into account the population rate, weather conditions and incident and accident rate. The traffic density can be anticipated from the population rate whereas the level crossing mode of operation could be inferred from the weather condition. GIS in level crossing control allows for traffic capacity to associate data to route segments and viewing of the selected routes. Furthermore, it allows for projecting the impact area for accidental scenarios directly on the map and providing data in real-time to emergency management in the event of an accident [21]. Thus, resulting in an extended version of the Petri nets model for the level crossing by associating the resources and system functions [20].

In contrast, the application of the deterministic and stochastic Petri nets (DSPNs) in controlling road traffic at the level crossing was suggested by Huang et al. The model was developed to address parallel road traffic at the rail-road level crossings. Therefore, vehicles whose head is perpendicular and parallel to the level crossing zone were treated as the direct critical scenario and indirect critical scenario, respectively. The urban traffic lights were modelled by state charts which included eight, six and two phases [64]. Furthermore, traffic light control system could only start if its signals are all at danger or red state. The proposed solution was constrained by time delay of about 2s for changing the phases in addition to simultaneous green signal for direct and indirect critical scenario [64]. Thus, upper limit of the number of tokens that each lane in the PNs hold correspond to finite capacity net [64]. Capacity constraint rule called the strict transition rule ensured that the number of tokens in each output place does not exceed the maximum capacity after firing.

Furthermore, DSPN model included rail-road level crossing control system with a single and double track lines. Immediate transition firing was implemented for train detection at the activation point of the single track line network [64]. However, a state was implemented for double track lines in order to allow two different trains to simultaneously pass through the rail-road level crossing system. In addition, inhibited arc was applied to avoid train to train collision [64]. The control policy was used to avoid concurrent direct and indirect critical scenarios in the event of dynamic alternation of the traffic

lights while the train approaches the level crossing [64]. Thus, traffic control policy dependent on the order of the traffic signal lights, triggering of signals on the approach of the train and normalisation of signals as the train pass the crossing [64]. The limitation with the DSPN model is the interruption resulting from the conflict developing between simultaneous firing of the deterministic and immediate transitions [64].

A timed Petri nets (TPN) based control architecture for the rail-road level crossing has been developed. The architecture was based on the global behavioural model formulated from the various interactions of the involved sub-system's dynamics. The interaction is modelled from the detection of the train at activation point until exiting the level crossing [2, 63]. Moreover, the model included time specifications for each process executed. The level crossing closure cycle were modelled as a transition depending on the direction of the approaching train [63]. Hence, the process to close the level crossing was triggered by the firing confirmation of the required elements availability [63]. In addition, the model prevented the short level crossing opening by ignoring confirmation with the absence of the train at the entry or exit of the rail-road level crossing danger zone [63]. Furthermore, control parametrisation involving the operational and safety requirements of the level crossing were postulated. The imposed constraints were speed restriction of 160 km/h within the rail-road level crossing area as well as minimal announcement delay and closing time of 22s and 30s, respectively.

Thus, the model assumed passenger and freight train of the same length but restricted to approach the level crossing at 140 km/h and 70 km/h, respectively. The control system synthesis was based on the supervision limit, anticipated-announcement and time-approaching announcement [63]. Hence, the supervision limit determined the earliest location at which the anticipated announcement can be given to avoid short rail-road level crossing [2, 63]. Conversely, anticipated announcement dealt with actual approach speed of the train. Finally, train-approaching announcement ensured optimality by limiting train announcement to 22s before it can reach the intersection zone [63]. The firing intervals to the transitions of the TPNs depended on the speed of the train. Furthermore, speed can be used to determining the delays of each train in achieving the required safe separation distance at the level crossings [63]. However, the use of real-time dynamics was recommended to improve results.

2.4 Validation and Verification methods

Improvements can be quantified by validation and verification. Moreover, that the level crossing system holds socio-technical and safety critical duality. Any loss of functionality on the rail-road level crossings may have catastrophic consequences such as fatalities, injuries, damage to assets and traffic disruptions [1, 15]. In addition, railway transportation shares this infrastructure with the other mode of transport which has different operation and management. Therefore, it is imperative that the rail-road level crossing systems or their solution be subjected to rigorous validation and verification processes [65, 66]. Validation is process of testing the system's functionality against the user requirement specifications whereas verification concerns itself with the establishment of the validity of system functionality. Limited literature exists in validation and verification of the level crossing system due to commercial purposes.

Validation and verification techniques have been outlined for level crossing with automatic protection system (APS). To make reference, Mekki et al presented validation and verification method for level crossing with automatic train protection comprising of four train sensors. Thus, three of the sensors were placed on the train's approaching direction and one on the exit direction of the rail-road level crossing [65]. Furthermore, anticipation and speed sensor were placed prior to the train detection sensor to check train approaching in the opposite direction [65]. As a result, the sensor arrangement was to avoid longer level crossing closing time. Train sensor in the approaching direction detects the arrival of the train and trigger the alarm for the warning lights to switch on and barriers to close [65]. Thus, train sensor on the exit direction detects the train leaving the level crossing area generating an alarm to disarm ATS [65]. Henceforth, validation of the APS was based on the short opening and long closing duration.

Automatic protection system is a time-constraint system due to the interaction of its sub-modules and the required temporal specifications [65, 66]. Therefore, the solution by Mekki et al suggested the extraction and population of APS's time specifications into the user requirement specifications. A repository comprising of the generic observation patterns to watch all common temporal requirements and classify them according to type was created. In the repository, each temporal specification was assigned an observer or watchdog based on their property [65]. Hence, validation and verification processes were followed to check and analyse safety issues. Mekki et al proposed the use of automatic techniques for verifying temporal logic of the transitions of the Petri nets

or finite automata. This method has been proven efficient by theoretical proving but Mekki et al suggested that it be complemented with further analysis. For instance, the proposed model checker issue a Boolean type of output (true or false) which can be further analysed to accurate assessment.

Furthermore, repository contained the identification and instantiation of the short closing duration and long closing duration. Thus, short closing duration requires that the rail-road level crossing be open for at least T_{min} units of time which represents the period of separation two successive closure cycle [65]. Therefore, short rail-road level crossing closing time should be forbidden before pattern is to check if the global "go down" command is not executable before T_{min} has elapsed [65]. A dichotomy search algorithm was used to find optimal value for λ which is a distance corresponding to T_{min} . Further, a large value of λ guarantees that the requirements are met [65]. The rail-road long level crossing closing duration is counteracted by setting the lower and upper bound of the closing time [65]. Hence, in a case that the rail-road level closing time falls outside the defined boundary values then requirement shall not be satisfied [65].

On the contrary, Dutilleu et al postulated two forbidden states in verifying the rail-road level crossing time. These states originated from the time specifications within a synchronisation structures and the presence of train at danger zone when barriers are open [62]. The latter was evaluated by the continuous automata where automaton state is described by a location and clock value [62]. In addition, the clock variable in automaton is assigned to each transition while the arc transition corresponds to an activated clock in a given location [62]. In order to avoid forbidden states, Cramer-Rao boundary was formulated such that the upper and lower bounds do not include the forbidden states [62]. Therefore, safety control was synthesized based on the interoperability of the networks [62]. However, the proposed method is limited by the insufficiency of the controllability of the transitions under the forbidden states in order to block evolution of time [62]. Hence, current developments are looking into the application of petri nets to validate the correctness and unavailability of the safety critical states [21].

Janota suggested a multi-agent system (MAS) model to validate and verify delays of the rail-road level crossing's warning system and the length of the approach section. The MAS model comprised of several autonomous, interacting agents which collectively were able to achieve a goal that is impossible for an individual agent to achieve [25]. Hence, MAS represents traffic at the rail-road level crossing as a system giving instruction to hundreds

and thousands independent agents (road vehicles, trains and pedestrian) all operating concurrently [25]. The behaviour of individual agent and system can be observed at micro-level and macro-level, respectively. Verification showed that the highest train's entry speed have no delay on protection system but requires the approach section to be furthest from the level crossing [25]. Similarly, the lowest train's entry speed have extended delay on the protection system with the approach section being closest to the level crossing [25]. This suggested that verification of optimal train's entry speed is critical in achieving minimal delay on the warning system at closest activation point.

2.5 Conclusion

Related works in rail-road level crossing system development have been presented. In addition, this chapter has provided an overview of the operation, control, validation and verification of the rail-road level crossing systems and solutions. Presented literature has also on drawn the improvement efforts made and highlighted the existing gaps. Although, human element has been identified as the leading cause of accidents at the level crossing it is imperative that technical limitations are equally addressed. The education, engineering and enforcement approach have been suggested in order to improve safety at the rail-road level crossing. Yet, less effort has been made in determining the relationship between long waiting at the rail-road level crossing and unintentional violation of the traffic rules by users. Moreover, the underlying presented literature point out the gap on the rail-road level crossing capacity and safety improvement with railway traffic heterogeneity. Therefore, the present aims to address the gap through the application of convex optimisation in minimising the level crossing closing time amidst heterogeneous railway traffic.

Chapter 3

Level Crossing Data Analysis

This chapter presents spatial, temporal and behavioural analysis of the rail-road level crossing systems. The purpose of the data analysis is to identify factors affecting safety and capacity of the level crossings found on the southern corridor of the Western Cape metro rail. In addition, the impact of the identified factors is illustrated and analysed. The chapter is structured as follows. Introduction is given in section 3.1 followed by a brief description of the topographical layouts of the rail-road level crossings under study in section 3.2. The examination of the spatial factors is found in section 3.3. Furthermore, analysis of the temporal factors is outlined in section 3.4. Behavioural analysis of the train drivers, motorists, cyclists and pedestrians at the rail-road level crossing is presented in section 3.5. Lastly, conclusions are given in section 3.6.

3.1 Introduction

The rail-road level crossing marks the point of shared use between the railway and road traffic. However, it also represents an accident hotspot to the railway transportation system. Rail-road level crossings are socio-technical systems because of the recurring complex interaction and interdependencies of human and technical elements. In addition, the rail-road level crossings are regarded as safety critical. Thus, socio-technical and safety critical duality of these systems is one of the reasons that they remain a challenge to date. Thus, it is imperative to understand parameters of the rail-road level crossings and their impact. In particular, considering the rate at which both the railway and road mode of transportation are evolving. Railway transportation has limited control over road users at the level crossings. Therefore, addressing systems such as these is critical

to railway transportation if it is to improve its competitive advantage [13].

Thorough knowledge of the advantages and drawbacks of the rail-road level crossing systems such is critical. It enables early detection of anomalies thus prompts quick response. Moreover, it allows smooth improvement processes. The advancements in transportation systems are directed towards mobility-as-a-service implying that there is high likelihood of significant increase in the railway traffic capacity in order to meet the user demand. However, an increase in railway traffic capacity is an anomaly which could deteriorate safety and road traffic capacity at the rail-road level crossing if not addressed in advance. Thus, studying incidents at the rail-road level crossing can be advantageous in determining the safety risks. Nevertheless, it is equally important to explore other elements or factors which may not be evident in risk assessment.

The existing literature has been focused in safety at rail-road level crossing but an inclusive approach is required. Safety improvements approaches such as EEE (Engineering, Education and Enforcement) and some have expanded this to 5Es (Enabling, Engineering, Education, Enforcement and Engaging) have been proposed [53]. This led to the establishment of projects such as SELCAT (Safer European Level Crossing Appraisal and Technology). The SELCAT project has successfully established four detailed classifications of accidents causes at the rail-road level crossings. The classes included rail-side human causes, road-side human causes, rail-side technical causes, road-side technical causes [53]. In addition, the project concluded that about 91% of the accidents are caused by human factor. Furthermore, about 80% of these reported accidents are attributed to inappropriate behaviour by road users [53]. The study further postulated that road user behaviour can be intentional and unintentional. However, majority of the rail-road level crossing accidents are due to intentional human error [53].

Therefore, it is imperative to conduct analysis of the rail-road level crossing before any improvement can be made. Primarily because of the socio-technical and safety critical duality of the rail-road level crossing systems. Hence, all elements must be addressed in order to achieve best system outcomes. Moreover, customised approach should be adopted when dealing with rail-road level crossing design and optimisation. The variations at the rail-road level crossing plays crucial role in examining the protection system efficiency. To make reference, the application of unimodal or multi-modal protection is specific to each rail-road level crossing system. Thus, the decision of which type of protection to apply should be based on accurate knowledge of parameters of each rail-

road level crossing system. In addition, efficiency of the level crossing not only depends on the operation of the protection system but also on the controller capability. The level crossings under analysis use track occupancy supervision control mechanisms. A brief overview of the track occupancy supervision and the axle counter train detection is given in 3.1.1 and 3.1.2, respectively.

3.1.1 Track Occupancy Supervision

In any railway network, train movements are monitored by track occupancy supervision. The same process is applied in the control of the protection systems deployed at the rail-road level crossings. The rail is segmented into finite track sections delimited by at least two axle counters. Hence, train movement in the railway network is supervised by the status of the track section. A track section can assume any of the three statuses at a time. These are 'occupied', 'free' and 'disturbed'. The rail-road level crossing system control is primarily based on the activation and deactivation tracks. Thus, protection system is enabled when the activation track is 'occupied' and withdrawn when deactivation track is 'free'. A 'disturbed' track section does not trigger any action on the protection system as the level crossing is already operating in degraded or emergency mode.

The layout of the level crossing system is depicted in Figure 3.1. The operational strategy adopted for the level crossings under study involves preparing for the approaching trains at most two signals prior to the crossing. According to the layout in Figure 3.1, protection system is activated as the train is detected at t_a and deactivated once the track section t_d is 'free'. Additional pre-activation conditions may require time delay on S1 and S0 upon the occupation track section t_{s1} and t_{s1} , respectively. The illustration of the sequence of events as the train approaches the level crossing is shown in Figure 3.2. The red marked segment indicates train occupancy and the green mark along the track sections indicates anticipated train routing. A route has a departure and destination signal, and it is only available once the departure signal is at a proceed aspect (yellow or green). Furthermore, the passage of a signal at red (danger) is regarded as SPAD which is a serious non-conformance in railway as it can result in train collision. Thus, elements (signals or track sections) normalises when in not use to indicate their availability.

Signals (S0) located right beside the level crossing is termed the protecting signal. Therefore, a signal S1 is limited to a yellow aspect to ensure that trains adhere to a speed

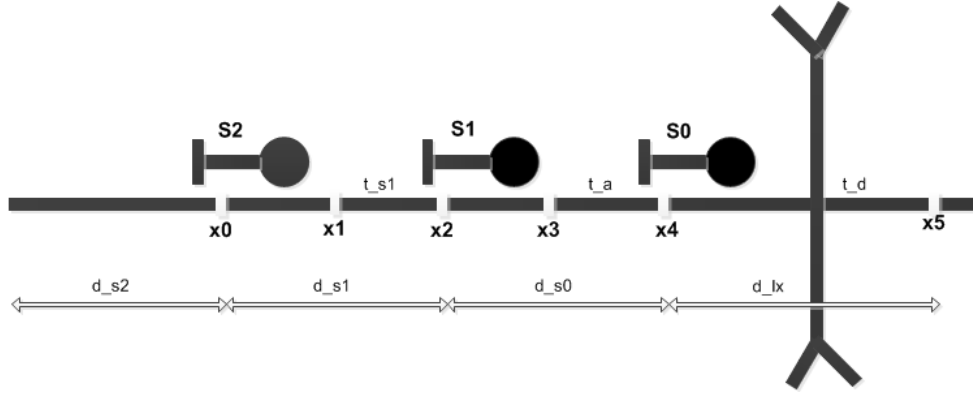


Figure 3.1: Layout of rail-road level crossing

restriction of 30km/h when arriving at S0. As the train enters the activation track either a track down or time release approach is applied. Thus, a track down activation approach requires the train to occupy the approach track t_a prior to clearing the protecting signal or route over the rail-road level crossing. Similarly, time release is an extension involves time delay on the signal whose approach track is occupied. The rail-road level crossing indication changes colour to reflect its status. Time release is applied in a case where S0 and S1 placement does not support the required braking distance otherwise track down is applied. The black indication on the level crossing reflects that the road users have right of way over the level crossing, as shown in Figure 3.2. The level crossing marking changes to yellow as the train occupy the activation track signalling the activation of the protection system, as shown in Figure 3.2. Once, the level crossing is armed and secured the indication stop flashing. Likewise, the indication changes to red when the train enters the level crossing's danger zone as depicted in Figure 3.2. Finally, the level crossing normalises once the deactivation track t_d is declared 'free' as shown in Figure 3.2.

The rail-road level crossing system is an open loop control system where the induced voltage of the track section of interest serves as an input to the controller. Train detection technologies sense the train as it traverses and send this information to the controller. Henceforth, the protection system lowers the barriers in addition to warning lights and siren. Latency time associated with lowering of the barriers is at most 10s under normal operation. Whereas, flashing lights and siren provide immediate warning when actuated. Studies have shown that reaction time of 2s is sufficient for the road users to respond to the warning system [15]. Moreover, multi-modal protection system has been proven proactive in ensuring safety at the rail-road level crossings [4].

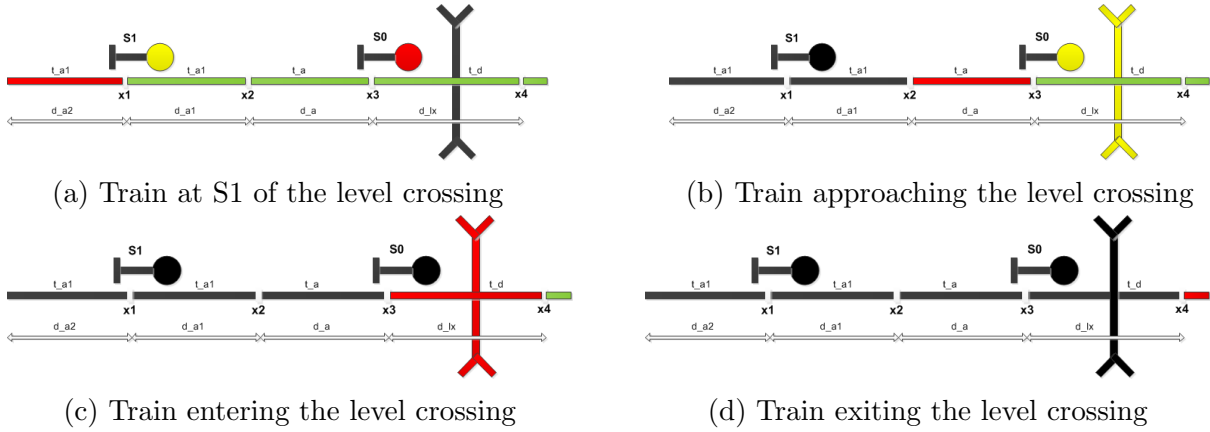


Figure 3.2: Sequence of events occurring at the level crossing

3.1.2 Train detection: Axle Counting

Axle counter is the most applicable train detection in an electrified railway network. Thus, axle counter use the count in and count out of the train axles principle in detecting train [55, 57, 59]. Track occupancy is established when the train's first set of axles are detected and this status is assumed until the all axles are counted in are counted out on the adjacent detector. As a result, at least two axle counter detectors are required to successfully detect the train. The axle counter train detection overview is shown in Figure 3.3. Thus, each detector is equipped with a transmitter and receiver to support bidirectional train movement and determine the direction of travel. The axle counter technology uses distortion on the magnetic flux linkage between the transmitter and receiver coils to detects the presence of train [55, 57]. Therefore, status of the axle counter track section is defined as follows:

Free: the number of axle counted in equals the number of axle counted out.

Occupied: the number of axles counted out is less than the number of axle counted in.

Disturbed: the number of axles counted out exceeds the number of axle counted in but also include faults such as communication breakdown or power failure.

Furthermore, axle counter train detection system comprises of sensor coil, electronic junction box and evaluator, as shown in Figure 3.3. Sensor coil consists of transmitter and receiver coils. The sensor coil is mounted onto the rail to enable train detection. The signal received from the sensor coil is conditioned by the electronic junction box to necessitate axle counting. Henceforth, an evaluator determines the track status by comparing axles count in and count out data. In addition, an evaluator communicates

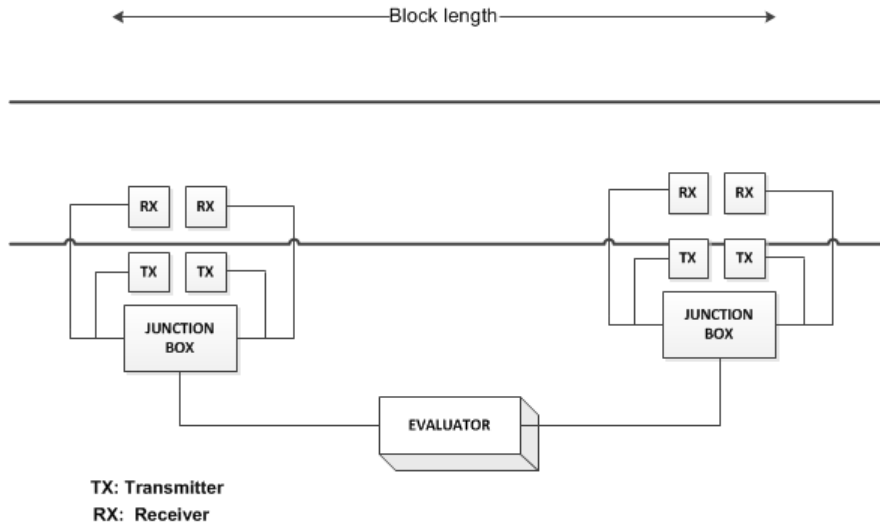


Figure 3.3: An axle counter train detection system

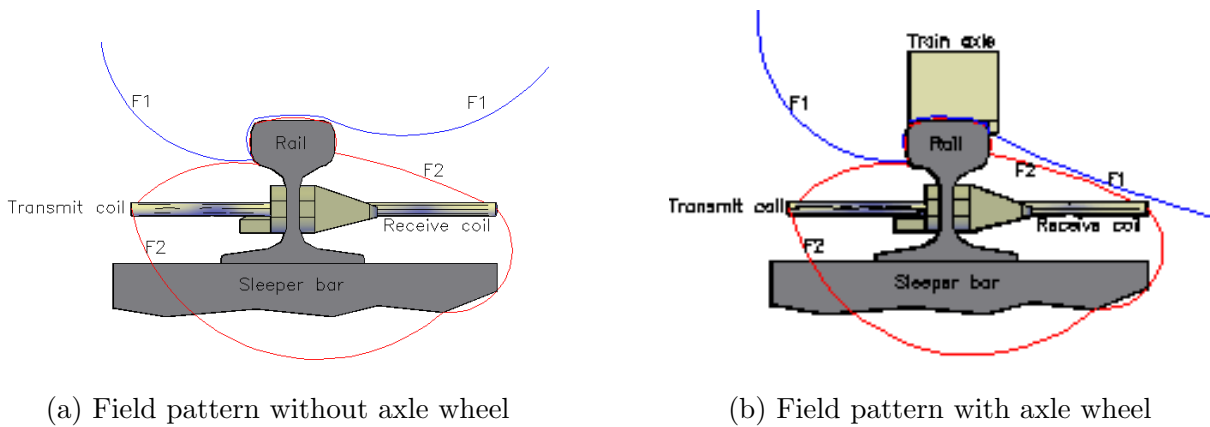


Figure 3.4: Train detection by axle counter sensor

the track status to the control room for track occupancy supervision. The axle counter uses electromagnetic principle to detect the train. Magnetic flux is generated on the transmitting coil and the flux flows through the path with low reluctance [55], denoted by F1 and F2 in Figure 3.4a. As the train wheel is detected, magnetic flux get distorted resulting in less flux flowing on the receiving coil [55]. This results in less induced voltage on the receiver, as depicted in Figure 3.4b.

The passage of train axle is determined by continuous monitoring of the changes in the induced voltage on the receiving coil relative to the set threshold voltage [55]. Therefore, train detection is established when the amplitude of the induced voltage is less than the threshold voltage. However, the effect of noise on the induced voltage could result in detection failure. The difference in the induced voltage in the absence and presence of train (δV) has to be sufficiently large counteracted in order to reduce the noise effect [57]. In addition, induced voltage on the receiver depends on the orientation of the coils for accurate detection [57]. Though axle counters are unsusceptible to interference, they susceptible to memory loss during power failure.

Moreover, the power failure on the axle counter has a potential to damage of the memory circuit storing the occupation status of the track section [55, 57]. This can be catastrophic when power failure occurs immediately after a train entered a new track section or a block in the absence of backup power. In this case, the status of a track section is unknown upon the restoration of the power and conditional reset is required to ensure safe transit operation. The effect is minimal for simple and small railway network and adverse for complex and large railway networks. In addition, the effect can be huge for safety critical systems such as the level crossings. Particularly in the case where the power failure occurs as the train approaches the level crossing.

3.2 Topographical layout

There are nine rail-road level crossings along the southern corridor of the Western Cape metro rail, as shown in Figure 3.5. However, in this study only eight of these level crossings are considered. In addition, these level crossing are within 20km section of the entire corridor length of 45km. Topographical variation of the identified rail-road level crossings is evaluated to assess operational and safety constraints. The schematic



Figure 3.5: Southern corridor of Western Cape metro rail

layout and the operation of each of the level crossing are outlined. Railway signalling system deployed at the level crossings under study supports bidirectional operation but only unidirectional operation shall be considered. Hence, traffic directed to the right shall refer to No.1 suburban line whilst traffic is directed to the left shall refer to No.2 suburban line.

3.2.1 Austell Road

Austell road is located in close proximity to the halt station (Heathfield) depicted in Figure 3.6. This level crossing is equipped with warning lights and half booms for protection. Thus, protection system is triggered by the occupation of the track section 3360T or 3962T on No.1 suburban line and No.2 suburban line, respectively. In addition, the activation track section along No.1 suburban is at a platform of Heathfield halt station. Deactivation of the level crossing's protection along No. 1 and No.2 suburban line occurs when the train exits track section 3460T and 3462T, respectively. The protecting signal 3440 has green as its highest aspect. This implies that trains are allowed to enter and exit the level crossing at maximum line speed provided that speed restriction of 30km/h is adhered over the level crossing. However, the system has no means to ensure that speed restrictions are followed thus it relies on the driver to act accordingly. Similar aspect conditioning applies along No.2 suburban line again it remains the train driver's

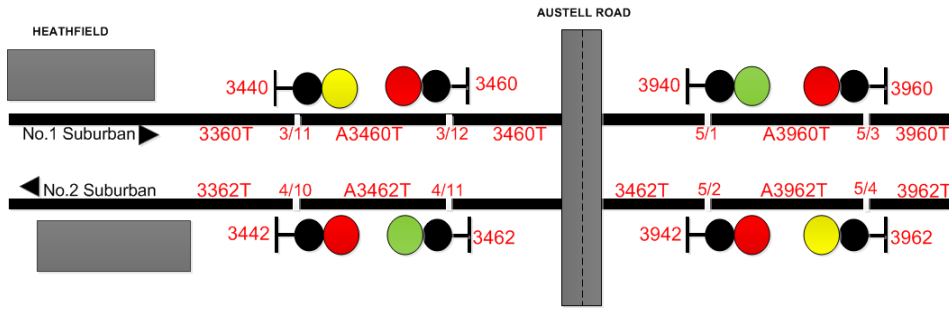


Figure 3.6: Layout of Austell road level crossing

responsibility to adjust the train speed based on whether the train stops or pass adjacent platform.

3.2.2 White Road

White road level crossing is located in close proximity to Military road, as depicted in the schematic in Figure 3.7. Its protection system comprises of two sets of flashing lights and two half booms. Along No.1 suburban line, level crossing activation is triggered by train detection over track section 4260T and deactivation is initiated once the train clears track section A4760T. The occupation of track section 4762T and clearing of A4762T along No.2 suburban line will activate and deactivate the level crossing's protection system, respectively. Furthermore, aspect conditionings on No.1 suburban line limits train movement to at most 30km/h past signal 4740. In addition, a time delay of 15s is imposed on signal 4740G after track section 4260T is occupied. This is to ensure safe braking of trains for arrival at signal 4840. However, No.2 suburban line supports exit of the level crossing at maximum line speed, provided that the train adhere to speed restriction of 30km/h at the crossing.

3.2.3 Military Road

The point machine set (4821W and 4831W) add flexibility to the rail traffic by increasing accessibility of the rail-road level crossing, as shown in Figure 3.7. However, point machine presents discontinuity on the railway line which often limits the availability of the railway network. Military road level crossing is equipped with two flashing lights and two half booms as a means of protection. Hence, activation is triggered by occupation of track section 4760T and 4862T along No.2 suburban line. Equally, deactivation is triggered when a train clears track section 4831T on No.1 suburban line and track section 4821T

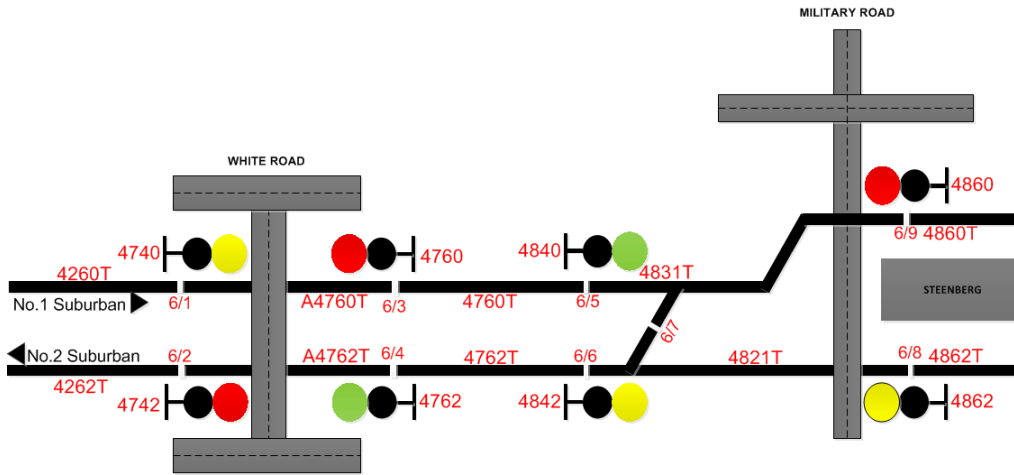


Figure 3.7: Layout of White and Military road Level crossings

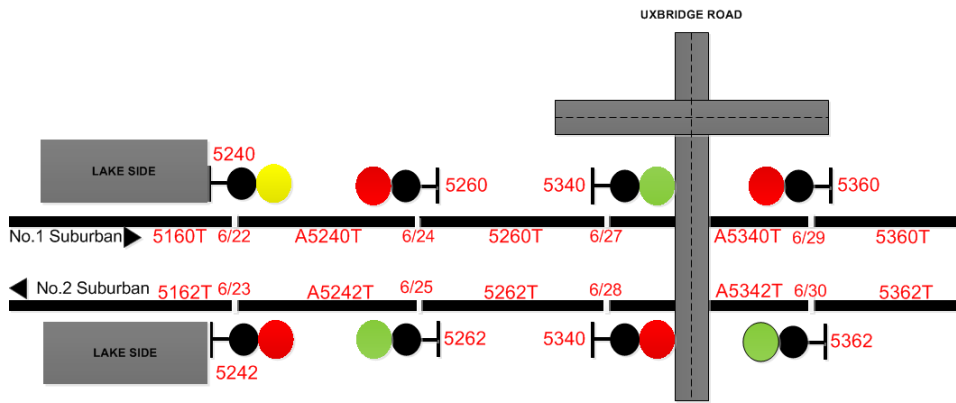


Figure 3.8: Layout of Uxbridge road Level crossings

on No.2 suburban line. Trains are only allowed to travel at cautious speed over the crossing side of a point machine set in order to reduce wearing and tearing effect. Thus, any crossing train movement shall have their depart signal at yellow aspect. Along No.1 suburban line, signal 4840 has a green as the highest aspect however due to the platform being closer to the level crossing trains are unlikely to travel at maximum line speed past signal 4840. Thus, it remains the train driver’s responsibility to adhere to the speed restrictions. Train’s speed is limited to at most 30km/h along No.2 suburban to ensure safe braking for arrival at signal 4762. An additional time delay of 15s before signal 4862 can clear upon the occupation of track section 4862T.

3.2.4 Uxbridge Road

Uxbridge road level crossing is protected by flashing lights and two half booms. Along No.1 suburban, the protection system is enabled upon the occupation of track section 5260T and disabled when A5340T is cleared. However, along No.2 suburban line activation

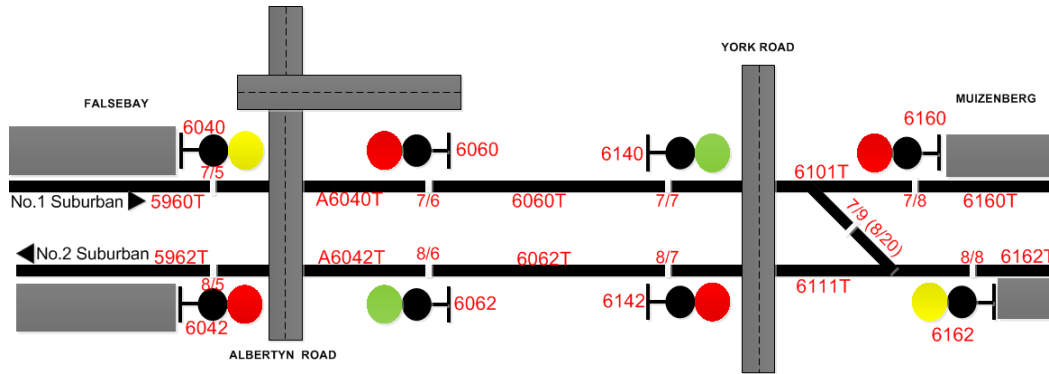


Figure 3.9: Layout of Albertyn Road Level crossing

is triggered by the train occupation over track section 5362T and deactivation is triggered when the train clears track section A5342T. Highest permissible aspect for the protecting signals on both lines is green. Furthermore, additional time delay of 15s is imposed on signal 5340 and 5362 following activation trigger. The speed restriction of 30km/h over the level crossing must be adhered in spite of the aspect displayed on the protecting signal.

3.2.5 Albertyn Road

Albertyn road is protected by two sets of warning lights, two half booms and pedestrian gates. It is located in close proximity to York road as depicted in Figure 3.9. The occupation of track section 5960T and clearing of A6040T along No.1 suburban line activates and deactivates the protection system protection system, respectively. Likewise, train detection over track section 6062T initiates the level crossing activation whilst the normalisation of A6042T deactivates the protection system along No.2 suburban line. Signal 6040 is limited to a yellow with a time delay of 15s upon the occupation of the activation track 5960T. Lastly, highest permissible aspect on signal 6062 is green thus it remains the train driver's responsibility to adhere to 30km/h speed over the level crossing.

3.2.6 York Road

York road is a pedestrian crossing equipped with two sliding gates within a barricaded zone. As shown in Figure 3.9, the protection system is activated upon the occupation of track section 6060T and 6162T along No.1 suburban line and No.2 suburban line, respectively. Similarly, the protection system is deactivated when the train exits track

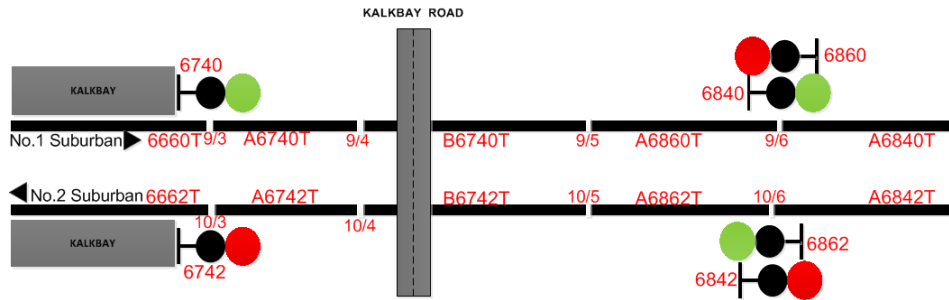


Figure 3.10: Layout of Kalkbay road level crossing

section 6101T along No.1 suburban line and 6111T along No.2 suburban line. The projected aspect sequencing for 6140 permits trains to depart protecting signal at maximum line speed but with speed restriction of 30km/h over the danger zone. In contrast, signal 6162 only permits train movements at cautious speed to ensure safe braking for arrival at signal 6062.

3.2.7 Kalkbay Road

Kalkbay road, shown in Figure 3.10 is protected by two full booms and two sets of flashing lights. Hence, the protection system is activated as track section 6660T is occupied and deactivated when track section B6740T is free of train occupation along No.1 suburban line. In addition, level crossing activation and deactivation along No.2 suburban line is triggered by the occupation of A6842T and normalisation of B6742T, respectively. The protecting signals on both lines have green as the highest permissible aspect however speed restriction over the level crossing still applies.

3.2.8 Beach Road

Beach road level crossing involves a single railway line, as depicted in Figure 3.11. Its protection system comprises of two half booms and two sets of flashing lights. The level crossing protection system is activated when a train occupies either 7742T or 8862T. Similarly, the protection system is deactivated when the train exits track section A7742T. Both protecting signals (7742 and 7762) have green as the highest permissible aspect, as shown in Figure 3.11. However, additional time delay of 10s is imposed on signal 7742 upon the occupation of track section 7742T.

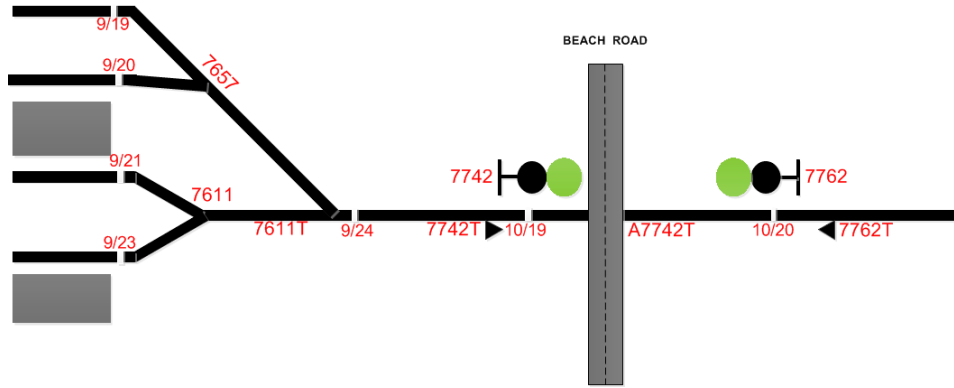


Figure 3.11: Layout of Beach road level crossing

3.3 Spatial Analysis

The rail-road level crossing exists within the railway and road space. Thus, spatial analysis is critical in determining the weakest point in the operating environment. The aim of this analysis is to identify and assess the impact of physical factors on the rail-road level crossing environment. Hence, in this study only common spatial features are considered and they are characterised into road-based and rail-based. The road-based spatial features include pavement condition, angle of rail-road intersection, level crossing area and visibility of the level crossing's protection or warning system. Similarly, the presence of the platform at activation, the length of rail section in which the level crossing reside, the rail profile and curvature are the rail-based spatial features considered in the study.

Pavement conditions have been identified as a one of the causes of road accidents. Thus, extensive literature has been focused on the examination of the relationship between the road surface and traffic safety. The common road surface parameters are the rut depth and the surface unevenness. Previous studies have reported that uneven road surface reduces traffic safety in comparison to the presence of ruts [67, 68]. The pavement condition is graded according to the rut depth and surface smoothness using three grades namely poor, fair and good. A smooth pavement with no ruts is graded 'good' whilst the uneven pavement with ruts is graded 'poor'.

The angle of intersection between the rail and road tend to affect road traffic flow the most. Moreover, large intersection angle may affect the visibility of activities happening at the level crossing. Hence, elevation angle at the intersection of the rail and road is extracted from Google earth pro tool. The rail-road level crossing area encompasses the

boundaries of the road and rail. Thus, the traffic volume (railway and road) guides the size of the rail-road level crossing. In addition, visibility of the level crossing is critical in ensuring that road users respond appropriately to the warning system. Thus visibility is characterised as "obscure" if the train cannot be seen at activation point or "clear" if the opposite is true. The assessment of the road-based spatial features is listed in Table 3.1.

Table 3.1: Assessment of road-based spatial features

Level crossing	Pavement condition	Intersection angle	LC area	Visibility
Albertyn Rd	Fair	2°	$17.5m^2$	Clear
Austell Rd	Good	20°	$18.4m^2$	Clear
Beach Rd	Good	2°	$9.5m^2$	Clear
Kalkbay Rd	Fair	25°	$10.8m^2$	Obscure
Military Rd	Fair	2°	$24m^2$	Clear
Uxbridge Rd	Good	1.5°	$14.4m^2$	Clear
White Rd	Fair	4°	$19.2m^2$	Clear
York Rd	Good	1.5°	$4.4m^2$	Obscure

The assessment of the rail-based spatial features is listed in the Table 3.2. One of the rail-based spatial features is the presence of platform at or in close proximity to the activation point. A platform represents trains scheduled train stops. Therefore, the impact of the platform is cross dimensional and it shall be analysed in the coming sections. The significance of train detection in level crossing operation has been emphasized. Thus, axle counter is dependent on the orientation of the transmitter or receiver coil which is measured by the rail profile. Diameter (b) and height (a) of the mounting hole determines the orientation of the axle counter sensor coil. Hence, continuous rail wearing and tearing can affect rail profile and the orientation of the sensing coils. As a result, intermittent detection failures or voltage drift warning is inevitable [59].

Conversely, rail curvature can result in train derailment as well as wear and tear the rail. Furthermore, high rail curvature may affects train driver's sight thus presenting risk for SPAD incidents. Therefore, speed restriction is imposed at high rail curvature. Although not apparent, the number of railway lines at the level crossing has an impact on the closure duration. To make reference, simultaneous level crossing's entry or exit on multiple rail lines has less impact on closing time yet overlapping entry or exit has an opposite effect. Finally, the impact of the length of the section bounded by the activation and deactivation indicate the time spend at the rail-road level crossing per train trip. According to data presented in Table 3.2 regarding the length of level crossing, trains

should on average spend less than 60s over the level crossing. However, exception applies for Austell and Kalkbay road.

Table 3.2: Assessment of rail-based spatial features

Level crossing	Platform	Rail profile (bxa)	Curvature radius	rail lines	LC section length
Albertyn Rd	Yes	14mm x 64mm	936m	2	163m
Austell Rd	Yes	14mm x 63mm	351m	2	570m
Beach Rd	No	13.5mm x 63mm	211m	1	110m
Kalkbay Rd	Yes	15mm x 62mm	250m	2	484m
Military Rd	Yes	14mm x 63mm	563m	2	204m
Uxbridge Rd	No	12mm x 63mm	982m	2	135m
White Rd	No	13mm x 64mm	112m	2	131m
York Rd	Yes	12mm x 62mm	357m	2	110m

3.4 Temporal Analysis

Long waiting time has been identified as one of the technical factors contributing to accidents at rail-road level crossing [33, 53]. Thus, long level crossing closing time is evident at the rail-road level crossings with high road and rail traffic volume. This analysis examines factors attributing to long level crossing closing time. It has been reported that trains travelling at speed below expected maximum permissible speed and the controller inability to ensure that all safety parameters are met at higher train speed are the among factors contributing to long waiting time [31, 33]. The rail-road level crossing closing time is measured by the time difference between the occupation of the activation track and clearing of the deactivation track.

Temporal analysis of level crossings along the southern corridor of the Western Cape metro rail is conducted. The current interlocking system (L905) has the capability to record and report track side elements status in real time. Thus, track side elements such as axle counters, signals, point machines and level crossing controllers constantly feedback their statuses to the maintenance operator place (MOP) located at the central train control centre (CTCC), as shown in Figure 3.12. Communication between the CTCC and track side elements is facilitated by the interlocking module (IM) in the signalling equipment room (SER). In addition, the data logger (DL) stores this information locally

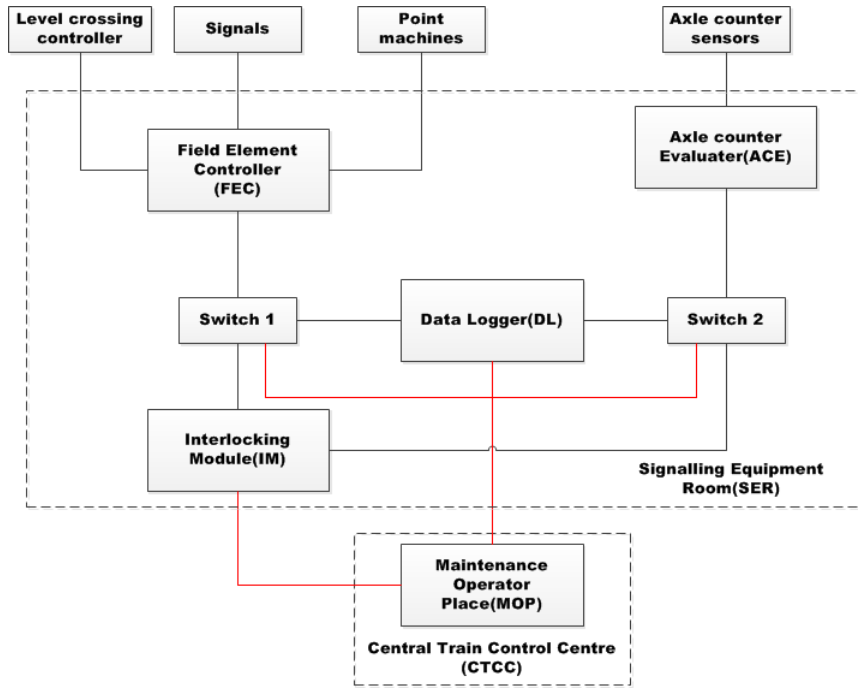


Figure 3.12: Thales L905 signalling system: Data flow diagram

and at the CTCC for backup.

Furthermore, interlocking system assesses the status and safety of events concerning the track side elements on the request from the CTCC. This accomplished through a bidirectional data transfer between the track side elements and IM. The same framework is used to report the statuses of the elements to the data logger for storage. MOP can displays real time events and statuses of the track side elements and replay history of events.

For this analysis, log files from 22-03-2019 until 11-04-2019 were collected and analysed. However, only axle counters involved in the rail-road level crossings is considered. Moreover, time stamp associated with activation and deactivation tracks are used however the analysis excludes track sections in faulty state. Furthermore, analysis is conducted using python in the Jupyter notebook.

Temporal variation between the level crossings under study is critical in identifying key elements affecting the closing time. The average closing times of the level crossing is listed in Table 3.3. Hence, a notable difference between the calculated and expected average closing time is observed. According to the level crossing topologies presented in

section 3.2, the anticipated level crossing closure durations should range from 45s and 155s. However, most of the average level crossing closing time listed in Table 3.3 far exceeds the expected results.

Moreover, the results presented indicate that on average about 24mins of the trip time along the southern corridor is spent at the level crossings. As a result, passengers are dissatisfied of the long travel time. Furthermore, there are safety and headway implications. Headway time is a determinant of the capacity of the railway network. It is defined as the time interval between two successive trains travelling in the same direction. Headway time along the southern corridor with 10% tolerance amounts to 170s.

Table 3.3: Average level crossing closing time

Level crossing	No.1 suburban: closing time(s)	No.2 suburban: closing time(s)
Albertyn Rd	290.4520	294.4435
Austell Rd	62.9735	106.8115
Beach Rd	185.2390	185.2390
Kalkbay Rd	249.7490	281.1825
Military Rd	303.3535	101.8080
Uxbridge Rd	76.2045	62.9735
White Rd	167.1625	163.1150
York Rd	212.2138	212.6353
Total	1410	1266

In order to examine the extent of the temporal variation, level crossings are categorised into two groups. The first group of level crossings has the average closing time below headway time (170s) and the second group has closing time above headway time. Scatter plot of the first and second group is depicted in Figure 3.13 and Figure 3.14, respectively. It can be observed that group 2 exhibits high irregularities in the closing time in comparison to group 1. Moreover, majority of the rail-road level crossings categorised in group 2 have platform at activation and time delay on the protecting signals in common. However, the same feature is present in some of the level crossings in group 1 then what is it that attributes a huge difference in the closing time between these groups.

Henceforth, the impact of the unique features in each class of the rail-road level crossing is explored. Beginning with group 1, the effect of the presence of the platform on the at the activation point on the level crossing closing time is shown in Figure 3.15. Austell road is

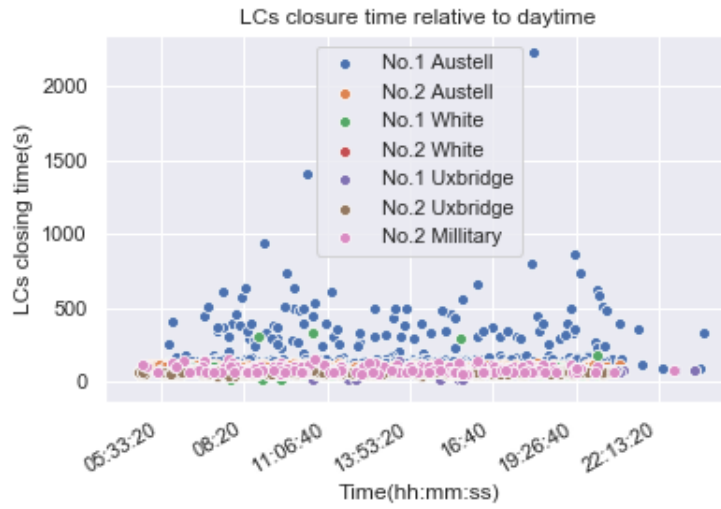


Figure 3.13: Level crossing with closing time below 170s

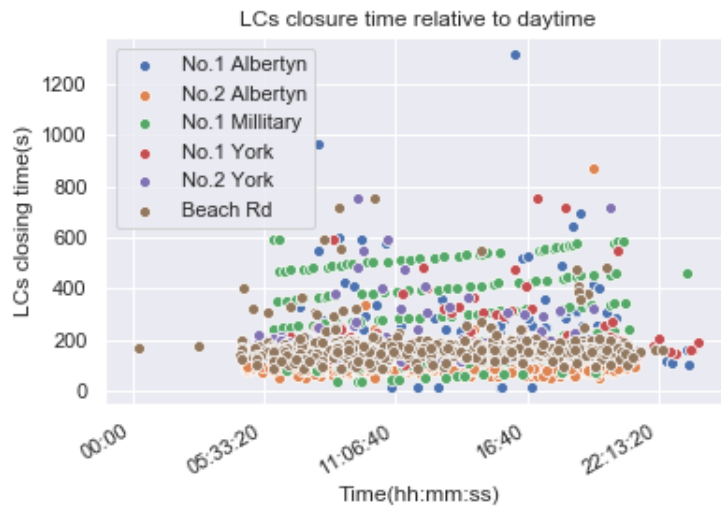


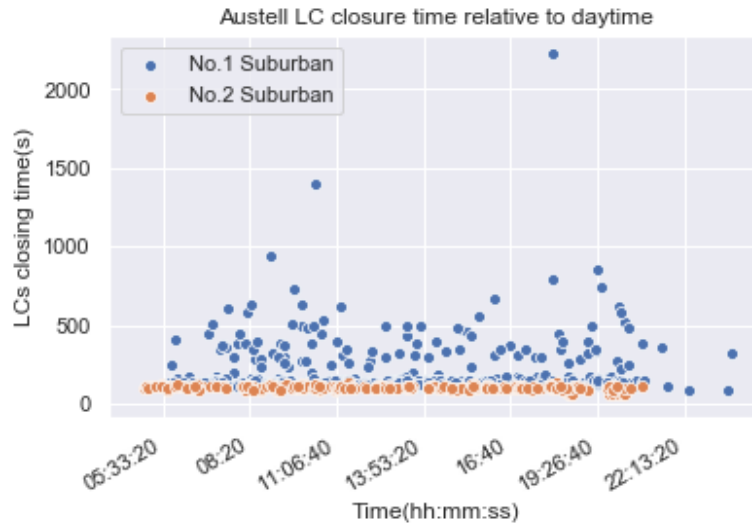
Figure 3.14: Level crossing with closing time above 170s

one of the level crossings in group 1 and it has the platform at activation only along the No.1 suburban line. It can be observed in Figure 3.15 that there is a huge disparity in the closing time along No.1 suburban line and No.2 suburban line. Moreover, the closing time along No.1 suburban exhibits sporadic pattern. This can be explained by dwell time associated with the platform. The time at which the train come to scheduled stop at the station or halt station's platform is called dwell time. Therefore, dwell time is dependent on the passengers flow rate in and out of the train. It is evident in Figure 3.15 that dwell time lead to irregularities in the closing time because it is not consistent with train trips.

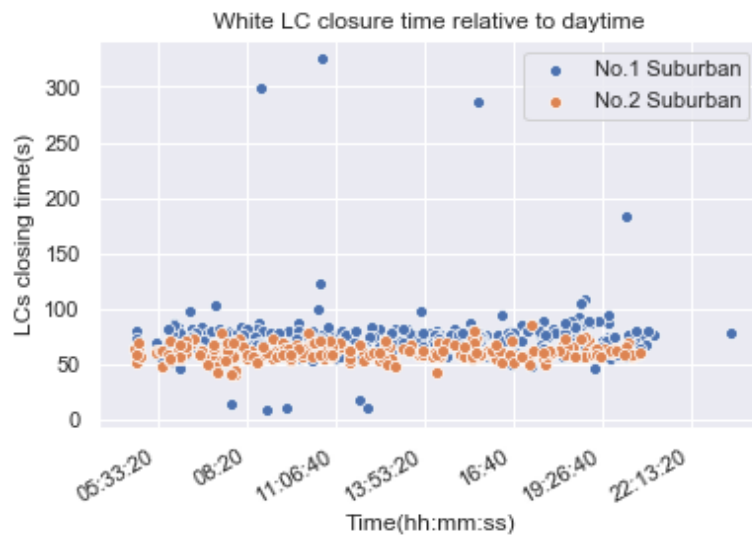
In addition, time release imposed on the protecting signal is the second common temporal feature in the considered level crossings. The effect of this feature on the group 1 level crossings is depicted in Figure 3.15. The distinguishing feature between No.1 and No.2 suburban line of White road is the time delay of 15s imposed on the protecting signal on No. 1 suburban line. Hence, this is evident by the small and uniform increase in the level crossing closing time. The outliers are attributed by the train driver's reaction time and train's speed on the approach of the protecting signal.

Lastly, some of the level crossings are approached from a scheduled stop on the closing time. In this case, the platform is located on the approach track section of the signal before the protecting signal (S1 in Figure 3.1). In group 1, trains approach Uxbridge level crossing from a scheduled stop at Lake Side halt station along No.1 suburban line. The irregular pattern on the closing time in Figure 3.15 is attributed to approaching the level crossing from a scheduled stop. However, the irregularities is not extreme such as in Figure 3.15. Approaching the level crossing at scheduled stop implies that the train's entry speed will be lower than expected.

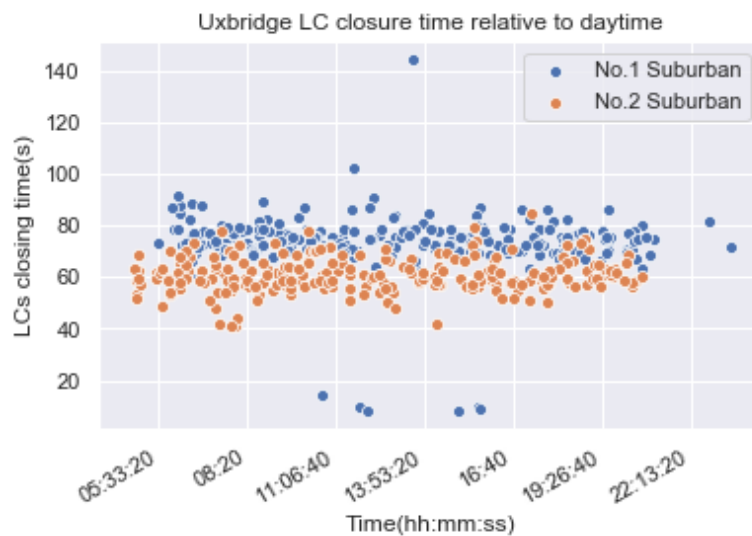
Drawing attention to group 2 level crossings, as previously mentioned an absurd pattern has been observed in spite of having the similar temporal features as the group 1. It turned out that group 2 level crossings have at least two of these parameters co-existing. In order to examine this further, the effect of the platform at activation and time delay on the protecting signal is assessed. Albertyn level crossing has a platform and time delay of 15s on the protecting signal along No.1 suburban line. The effect of dwell and delay time is indicated by the prolonged and irregular level crossing closing time, as shown in Figure 3.16. Likewise, the effect of approaching the level crossing from a scheduled stop combined with time delay on the protecting signal is analysed.



(a) The presence of a platform at the activation track



(b) Time delay on the protecting signals



(c) Approaching the level crossing from a scheduled stop

Figure 3.15: The effect of temporal features on the level crossing closing time

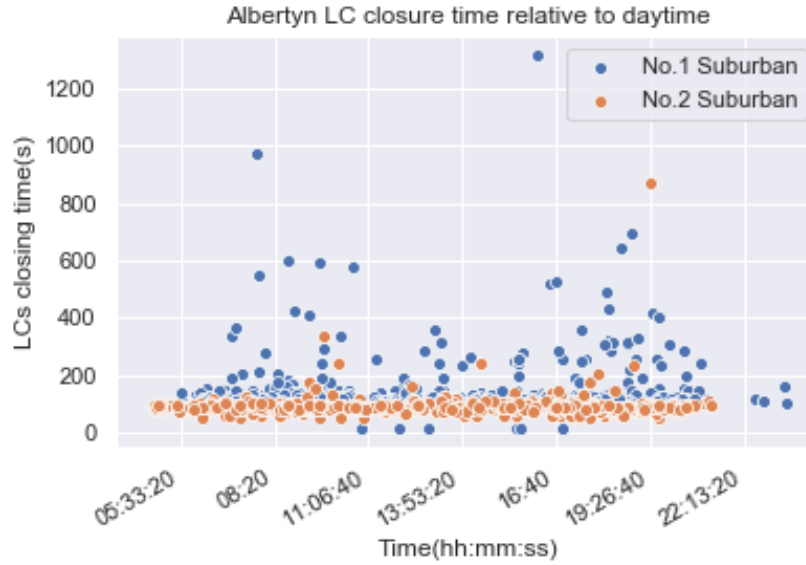


Figure 3.16: The effect of dwell and delay time on the level crossing

Beach road is approached from a scheduled stop for train movement to the right in addition 15s time delay is imposed on the protecting signal. Similar scenario is present along Albertyn level crossing along No.2 suburban line. Results depicted in Figure 3.16 and Figure 3.17 show prolonged level crossing closing time but with less irregularities. Furthermore, the results shown in Figure 3.16 indicate that the dwell time with time delay on the protecting signal has greater impact than approaching the level crossing from a scheduled stop with the time delay on protecting signal. Kalkbay road is the only level crossing in group 2 which has no co-existence of at least two temporal features. However, the only distinguishing feature is the application of the full booms in the protection system. Thus, the effect of applying full booms in the level crossing protection shall be elaborated on section 3.5.

The presented results suggest that irregularities in level crossing closing time are attributed to the dwell time associated with activation track at the platform. Dwell time is one of the constraints of the capacity of railway system. The challenge with dwell time is that it is uncontrollable due to its dependency on the passengers flow rate. The analysis proved that when associated with level crossings the impact on the railway system's capacity may be adverse. Moreover, the average level crossing closing time affects capacity of the railway transportation system. The second temporal parameter contributing to longer rail-road level crossing closing time is time delay on the protecting signal. Hence in this case, an increase in the level crossing closing time is a compound of the time delay, train driver reaction time and the required acceleration time. Lastly, the application of the full booms on the level crossing protecting system tends to extend the closing time. Hence,

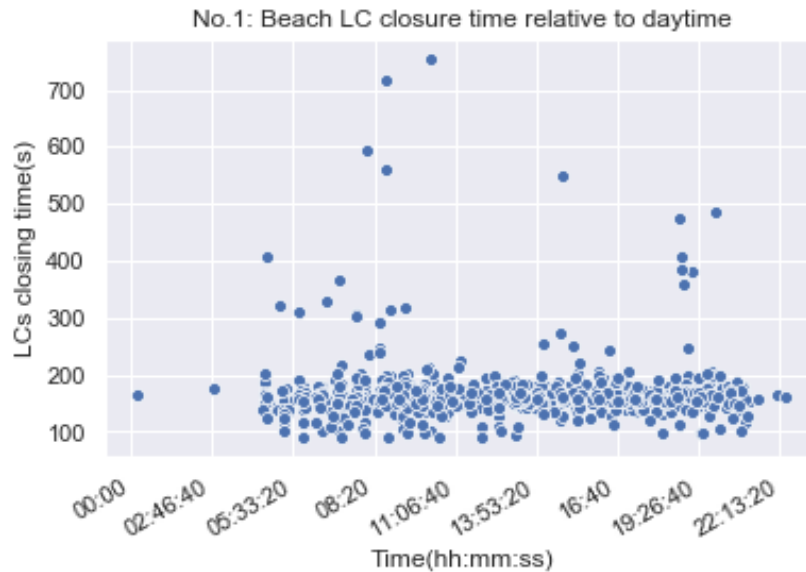


Figure 3.17: Approaching the level crossing with time delay from a scheduled stop

this effect shall be explored on the oncoming section.

3.5 Behavioural Analysis

Rail-road level crossing system requires interaction of human and technical element. Hence, the study human behaviour at the level crossing is critical in assessing the safety and efficiency of the system. Previous studies have identified human element as the leading cause to accidents at the rail-road level crossings. Thus, the objective of conducting behavioural analysis is to add to existing literature by assessing the link of the human and technical element with regards to the safety at the level crossings. This analysis is limited to the behavioural assessment of the railway traffic operators, train drivers, motorists, cyclists (or bikers) and pedestrians. Furthermore, only measurable behavioural attributes are considered in this study.

Behavioural conduct of motorists, cyclists and pedestrians is extracted from the video footage from the CCTV cameras. Each rail-road level crossing under study is monitored by two CCTV cameras which are mounted on a mast pole of 2m above the road surface. A week-long footage was used and objects detection software was applied to ease assessment. Misconducts were manually extracted and recorded for analysis. The behavioural analysis of railway operators was conducted on the GXD replay application available on the MOP.

GXD functionality allows for replay of the operational events at the selected time and location on the network. In addition, train driver's behaviour is extracted from a sequence of events following the point at which route is granted.

Measurable train driver's behaviour includes responsiveness to protecting signals and adhering to the speed restrictions over the level crossing. Hence, common unsafe acts committed by train drivers are passing signal at danger (SPAD) and exceeding 30km/h speed over the level crossing. Conversely, motorist's behaviour is measured by the level of response to warning given from the protection systems and refraining from stopping within the level crossing demarcated zones (or danger zones). Similarly, behaviour of the cyclists and pedestrians is measured by the ability to respond to warnings of approaching train. Warning includes flashing lights, sounding siren and closing of barriers.

The rail and road traffic operate differently thus large traffic density can affect capacity and safety at the level crossings. Railway traffic is dispatched in accordance with the set timetable. In the case of the eight level crossing considered, trains are dispatched every 25mins in each direction at peak hours otherwise they are dispatched on hourly basis. However, train timetable only holds when there are no train delays. Moreover, train delays can be categorised into primary and secondary. Primary delays are due to late departure of trains and may affect train schedule by few seconds or minutes. Therefore, no train cancellation may result from rescheduling due to primary delays. In contrast, secondary delays affect the timetable by hours which often result in cancellation of other train trips. Table 3.4 gives the average traffic density at the level crossings per busiest hour.

The train passing signal at danger can be detected and recorded in L905 interlocking system. Therefore, SPAD is evaluated from the reported statuses of the level crossing protecting signals. Though train speed cannot be measured by axle counter sensors, it can be inferred from the trajectory and train detection data. Thus, train's speed can be calculated from the length and time difference between the entry and exit of the level crossing's island track/s.

A daily incident report has been compiled in Table 3.5. Incidents are evaluated on unsafe acts committed by each respective rail-road level crossing users. Passing the signal at red and exceeding speed restriction over the level crossing by the train drivers.

Table 3.4: Average traffic at the level crossings per hour.

Level crossing	Trains trips	Trucks	Buses	light vehicles	Cyclists	Pedestrians
Albertyn Rd	8	74	15	1500	35	700
Austell Rd	8	0	0	600	10	185
Beach Rd	8	0	0	490	15	100
Kalkbay Rd	8	0	0	650	1	200
Military Rd	8	30	21	3060	65	1574
Uxbridge Rd	8	0	0	850	45	250
White Rd	8	35	0	640	37	500
York Rd	8	0	0	0	0	300

In addition, road users are evaluated based on ignore the warning from the flashing lights. Furthermore, motorists are evaluated on stopping within the demarcated level crossing zone whilst cyclists and pedestrians assessed on crossing over closed booms. Therefore, assessing the number of the reported incidents relative to the traffic density and percentage of the incidents can give an indication of the safety level crossing.

Table 3.5: Incidents recorded at the level crossings.

Level crossing	SPAD	SR	M - IWS	M - SDZ	C - zigzag	C - SDZ	P - zigzag	P - IC
Albertyn Rd	1	0	69	145	13	1	35	20
Austell Rd	0	0	55	80	5	3	13	85
Beach Rd	0	0	34	55	5	3	19	13
Kalkbay Rd	0	0	125	45	8	10	50	22
Military Rd	0	2	661	292	23	6	156	1000
Uxbridge Rd	0	0	44	105	3	6	17	10
White Rd	0	1	60	47	4	11	54	185
York Rd	0	0	0	0	0	0	0	0

Where:

SPAD - Signal passed at danger by train driver,
 SR - Speed restriction adherence by train drivers,
 IWS - Intentionally ignoring warning,
 SDZ - Stopping within demarcated danger zones,
 IC - Illegal crossing of the railway tracks,
 M - Motorists,
 C - Cyclists and
 P - Pedestrians.

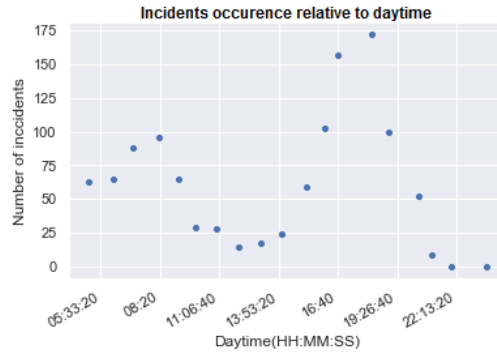


Figure 3.18: Incidents reported relative to daytime

Results presented on Table 3.5 show that railway sector conform to the level crossings safety rules because train drivers account for less than 0.1% of the recorded incidents. Train driver's compliance suggests that systemic process in place and the ability of the interlocking to detect unsafe acts such as SPAD plays significant role in ensuring safety. However, safety at the level crossing requires all stakeholders to take part. In addition, the results indicate that cyclists accounts for 2.8% of the incidents recorded. Similarly, pedestrians account for 46.49% of incidents recorded whereas motorists accounts for 50.7% of the recorded incidents. Assessing the number of incidents reported relative to the traffic density indicate train drivers have 10.7% chance of causing an accident at the level crossing.

Yet, motorists have 22.8% chance of causing accidents at the level crossing. Cyclists and pedestrians are at high risk of being involved in the accidents at the level crossing. Thus, cyclists account for about 48% risk of accidents at the level crossing whilst and pedestrians account for 44%. It can be inferred that safety at the level crossing decreases with an increase in traffic density. In order to emphasize this, comparison of safety at Military and Beach road is conducted. Traffic density at Military road is seven times (7x) higher than traffic density at Beach road. The risk associated with Military and Beach road is 44.8% and 20.3%, respectively. Moreover, barricading the level crossing reduces the risk of accident occurrence as evident on York road.

Train driver's behaviour cannot be studied in isolation therefore it is critical to assess the dependency between the railway traffic operators and train drivers. Reaction time of the operators and train drivers at the rail-road level crossing is listed in Table 3.6. The results at Kalkbay level crossing reveal inefficiency of railway operation at the rail-road

level crossings. The attributing factor is that Kalkbay level crossing is manned due to the deployment of the full booms. At the manned active level crossing, the railway traffic operator at the control centre operates route for the train and prompts the operator at the level crossing to close the barriers on the approach of the train.

Additional human element at a manned level crossing introduces delays which eventually elongate the closing time. Therefore, manned active level crossings are less effective. Furthermore, the results in Table 3.6 indicate that time delay on the protecting signals and the application of automatic train routing (ATR) over the rail-road level crossing with platform at the activation point have an influence on the train driver's reaction time. Automatic train routing algorithm sets the routes as per train schedule provided the availability of the required elements. Therefore, ATR will set the routes over the level crossing without checking that dwell time effect on the level crossing closing time. However, an operator can choose not to set the follow up route where dwell time is expected to increase level crossing closing time.

Table 3.6: Average response rate for rail traffic operation

Level crossing	Traffic operator	Train driver
Albertyn (down)	3s	5s
Albertyn (up)	2s	5s
Austell (down)	1s	6s
Austell (up)	2s	8s
Beach (down)	2s	7s
Beach (up)	1s	8s
Kalkbay (down)	45s	15s
Kalkbay (up)	41s	13s
Military (down)	2s	10s
Military (up)	1s	8s
Uxbridge (down)	1s	7s
Uxbridge (up)	1s	7s
White (down)	1s	4s
White (up)	1s	1s
York (down)	1s	1s
York (up)	1s	1s

To extend road user behaviour, incidents recorded before and after the passage of train at the level crossing are analysed. Cumulative sum of recorded incidents within 60s before and after the level crossing closure is presented in Figure 3.18. Results shown indicate that the number of incidents increases during peak times. However, more incidents are

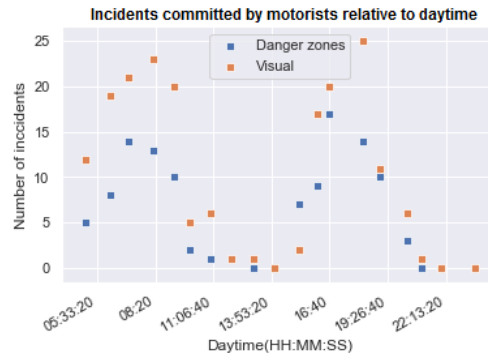


Figure 3.19: Incidents reported against the motorist relative to daytime

recorded within the 16:00:00 and 19:00:00 compared to between 06:30:00 and 09:30:00. Thus, there is some form of dependency between the increased traffic volume and human behaviour. Hence, human behavioural aspects such as anatomical, psychological, personal and social can be used to understand the disparity in the number of incidents at the two peak times.

In addition, incidents committed by the road users are broken down to each respective user. Therefore, incidents committed by motorists involve stopping within the danger zones and ignoring warning given by flash lights. The results of average number of incidents recorded in a day is shown in Figure 3.19. Thus, from the results it is evident that motorists tend to ignore the flash lights warning than to stop within the demarcated zones of the level crossing. Moreover, the number of incidents is high at peak hours. The comparison of the motorist's response to barrier and visual warning reveals that motorists are more responsive to the barriers as oppose to visual warning. Nonetheless, warning lights still serve an important role in the level crossing protection.

Figure 3.20 depicts the incidents committed by the cyclists within the stipulated window period of 60s prior and after the passage of train at the level crossing. The incidents are based on ignoring visual warning or flash lights and performing "zigzag" manoeuvres on closed barriers. Again, the number of incident is high at peak times. However, between 07:00:00 and 10:00:00 cyclists tends to ignore visual warning as oppose to the barrier. Yet, from 14:00:00 until 19:00:00 cyclists ignore both flashing and closed booms. This behavioural conduct emanates from factors such as fatigue, fear and stress levels of the individuals.

Pedestrians are evaluated on the criterion as cyclists. The number of incidents reported

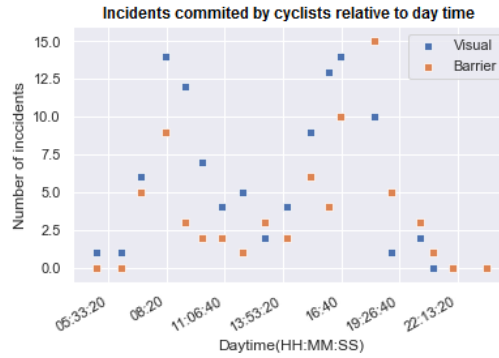


Figure 3.20: Incidents committed by cyclists relative to daytime

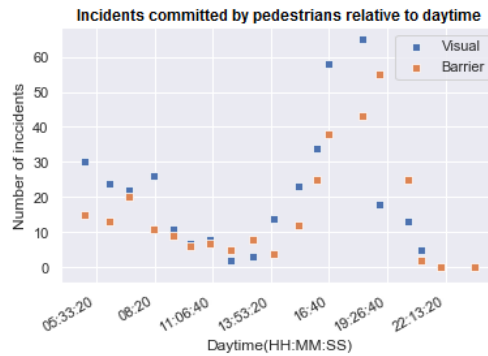


Figure 3.21: Incidents committed by pedestrians relative to daytime

is high at peak time particularly between 16:00:00 and 19:20:00, as shown in Figure 3.21. The results illustrate that pedestrians have the same level of response towards flashing lights and closed barrier. However, this trend is common at the rail-road level crossings with longer closing time.

Often, multi-modal level crossing's protection system is used to reinforce safety at the rail-road level crossing. In the unmanned active level crossing, the deployment of the protection system is initiated by the flashing lights followed by closure of the barriers within 5s to 10s period. Therefore, the response level of road users to the level crossing's protection systems is examined by monitoring user behaviour for about 60s after the train occupies the activation track. The obtained results are depicted Figure 3.22. It is notable that both pedestrians and cyclists are not responsive to the warning given by flash lights and barriers.

The lack of response by cyclists and pedestrians is evident on the number of incidents committed after 20s has elapsed. This is a psychological phenomenon, which is often stimulated by intolerance to long waiting time. However, it is seldom for motorists to

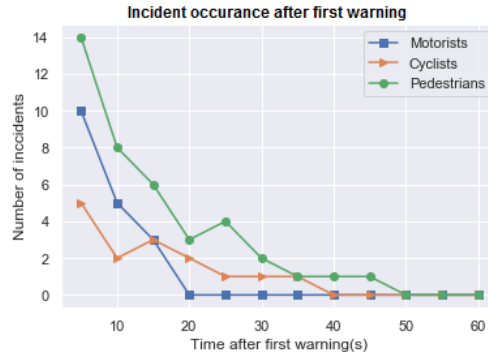


Figure 3.22: Behaviour observed 60s after level crossing activation trigger

engage in unsafe act 20s after the initial warning of the approaching train. Therefore, it is evident that motorists are more responsive to barrier protection system compared to the visual protection system. However, this highlights the failures in systemic processes to reinforce safety at the rail-road level crossing.

3.6 Conclusion

The complexity of the rail-road level crossing system originates from the socio-technical and safety critical duality. To add to this, is the reluctance to automated solution at the rail-road level crossing. Data analysis conducted indicates that rail-road level crossings are a safety and capacity concern. Furthermore, the outcome of the analysis reveals that some human element at these infrastructures can be directly or indirectly attributed to technical and environmental factors. Hence, rail-road level crossings with long closing time are at high risk of accidents. On average, train spends on average 24mins of its travel time along the southern corridor at the level crossings. This has implications on the safety and capacity of the railway and road traffic. In fact, majority of the level crossings have average closing exceeding headway time thus demonstrating the impact of level crossings on the capacity of the railway network.

Data analysis has been conducted to identify spatial, technical and behavioural features contributing to long closing time and compromising safety at the level crossing. Spatial analysis have shown that the presence of platform at or in proximity to the activation point have greatest impact of all the identified spatial features. Furthermore, the effect of platform is a cross-dimensional that its effect has been proved in the temporal and behavioural analysis. However, other spatial features can only have an effect under

degraded or emergency mode of operation hence it is important to account for them in the systemic process of the system mode of operation.

However, the findings of temporal analysis has illustrated that poor management of the dwell time associated with platform at activation can results in long level crossing closing time. Furthermore, approaching the rail-road level crossing from a scheduled stop has some effect on the closing time. Therefore, this suggest that the dwell time effect is not only observable at activation point but at the approach track of the signal before that protecting the rail-road level crossing. In addition, imposed time delays on the protecting signals have impact on the level crossing closing time. Finally, temporal analysis further indicates that the co-existence of at least two mentioned temporal parameters have drastic impact on both the safety and capacity of the rail-road level crossing system.

The study presented the assessment of the user behaviour. The railway operators and train drivers have shown highest compliance to the rail-road level crossing rules. However, the operators contribute to long closing time in manned rail-road level crossings. As a result, train driver's reaction to the protecting signal is affected by the delays introduced by operator in a manned level crossing. Furthermore, train driver reaction is affected by the time delay on protecting signal and the application of automatic train routing over the level crossing with platform. Behavioural analysis indicates that unsafe acts are common during peak times. In addition, the level crossing system susceptibility to changes in traffic volume particularly at peak times.

Motorists have shown to be responsive to the barrier protection system as oppose to flashing lights. In contrast, cyclists and pedestrians have shown to be less responsive to both visual and barrier protection system. Evidence presented suggests that systemic processes are critical in ensuring safety at the level crossings. To make reference, train drivers are more compliant to level crossing rules compared to other users due to systemic processes in place. Moreover, it is imperative to reduce time spent at the level crossings. Hence, the proposed optimisation solution must take into account train's entry speed, dwell time management and time release of the protecting signals. In addition, the solution must be robust against changes in traffic volume and patterns.

Chapter 4

Optimisation Solution

This chapter presents a brief overview of convex optimisation, its implementation in the level crossing closing time problem and the results obtained. The organisation of the chapter is as follows, a brief introduction of convex optimisation is presented in section 4.1. Mathematical modelling and solution formulation is found in section 4.2 and section 4.3, respectively. Implementation is presented in section 4.4 followed by the results in section 4.5. Concluding remarks are made in section 4.6.

4.1 Introduction

Application of optimisation techniques is common in railway transportation system. It has been applied extensively in area of railway traffic management problems such as scheduling and rescheduling. Moreover, modern automated railway systems are reliant on optimisation techniques. However, in the case of the present study optimisation of the rail-road level crossing is critical in ensuring optimal traffic control capacity and improved safety. Hence, convex optimisation is applied to find an optimal rail-road level crossing closing time for a heterogeneous railway traffic.

Convex optimisation was first introduced in late 1940s as a special case of linear programming. Its breakthrough is embedded on three methods named the simplex method, method of central sections and method of circumscribed ellipsoid. In 1947, simplex method was introduced for solving linear programming problems fitted on the scheme presented in

equation 4.1. These problems involved a feasible vector x for which $Ax \leq b$ form a polyhedron in \mathbb{R}^n [70]. A polyhedron may or may not be bounded but if bounded it is called convex polytope. By mathematical definition, a polyhedron is an intersection of finite number of half spaces. Hence, a linear function on the polyhedron set is at maximum at one of its vertices [45]. This implies that the maximum value of the linear function can be obtained by the largest value on the set of vertices.

However, the set of vertices can be large for real applications. Thus, systematic search method is required and it must be based on the assumption that the vertex is known and nondegenerate [73]. This means that n "linearly independent" inequalities of the vertex become equalities without any loss of generality [41, 45, 69].

$$\langle c, x \rangle \rightarrow \sup, \sum_{i=1}^n c_i x_i \rightarrow \sup \quad (4.1)$$

$$\langle a^j, \bar{x} \rangle = b_j, 1 \leq j \leq n, \langle a^j, \bar{x} \rangle \leq b_j, j \leq n + 1 \quad (4.2)$$

The vector $a^j = (a_{j1}, \dots, a_{jn})$, for $j = 1, \dots, m$ form a basis of \mathbb{R}^n in nondegeneracy. This means that the matrix $A_n = (a_{ij})_{1 \leq i, j \leq n}$ is nonsingular. Thus, by letting $\bar{b} = (b_1, \dots, b_n) \in \mathbb{R}^n$, then polyhedron is given by

$$A_n \bar{x} = \bar{b} = (b_1, \dots, b_n) \Leftrightarrow \bar{x} = A_n^{-1} \bar{b} \quad (4.3)$$

Solving out equation 4.3 reduces to

$$A_n^T \bar{\lambda} = c \quad (4.4)$$

Where: A_n^T is the transpose of A_n .

Applying the optimisation problem of a feasible vector x in $(Ax \leq b)$ and $\lambda = (\lambda_1, \dots, \lambda_n, 0, \dots, 0)$ results in the following nontrivial solution of the homogeneous system.

$$\langle c, x \rangle = \langle A_n^T \bar{\lambda}, x \rangle \leq \langle c, \bar{x} \rangle \quad (4.5)$$

Alternative possibility is obtained by allowing $\lambda < 0$,

$$\langle a^2, y \rangle = \dots = \langle a^n, y \rangle = 0 \quad (4.6)$$

However, due to the nonsingular nature of A_n then $\langle a^1, y \rangle$ is nonzero as shown in equation 4.7.

$$\langle a^1, y \rangle = -\varepsilon < 0 \quad (4.7)$$

Thus, for the small values of $t > 0$ the following is obtained

$$\langle a^j, \bar{x} + ty \rangle < b_j, j = 1, j \geq n + 1, \langle a^j, \bar{x} + ty \rangle = b_j, 2 \leq j \leq n \quad (4.8)$$

If the vector \bar{x} is feasible then the following should also be feasible

$$\langle c, \bar{x} + ty \rangle = \langle c, \bar{x} \rangle + t \langle c, A_n^{-1}(-\varepsilon, 0, \dots, 0) \rangle = \langle c, \bar{x} \rangle + t \langle (A_n^{-1})^T c, (-\varepsilon, 0, \dots, 0) \rangle = \langle c, \bar{x} \rangle - t\varepsilon\lambda_1 \quad (4.9)$$

This implies that $\langle c, \bar{x} + ty \rangle > \langle c, \bar{x} \rangle$ for all $t > 0$. However, if the $\bar{x} + ty$ is feasible for all $t > 0$ then the supremum of the problem is $+\infty$. Otherwise, $\langle a^j, \bar{x} + t_0y \rangle = b_j$ for some value t_0 of t for $j \geq n + 1$ such that $\bar{x} + t_0y$ is equivalent to \bar{x} . This is known as the nonsingular nondegenerate simplex method for numerical optimisation.

It was late in 1962 that the method of central section was developed as an algorithm that minimise a sum of exponentials (with positive weights) on a compact polyhedron [70]. The problem was posed as finding the minimum of a convex and quasi-convex function f on a finite-dimensional convex body A as expressed in equation 4.10.

$$f(x) \rightarrow \inf; x \in A \quad (4.10)$$

Equation 4.10 denotes a general problem of convex optimisation. If A is denoted by A_1 , then the centre of gravity of A_1 is given by $x_1 = grA_1$. Therefore, the solution is attainable if and only if $f'(x_1)$ is a zero vector. However, for the nonzero case then part

of A_1 in the half space $\prod_1' = \{x | \langle f'(x_1), x - x_1 \rangle > 0\}$ is eliminated. For convex f , then it can be shown that $f(x) - f(x_1) \geq \langle f'(x_1), x - x_1 \rangle$ in contrast to $x \in A_1 \cap \prod_1'$ where $f(x) > f(x_1) > \min\{f(x)\}$.

If ξ_m point of (x_1, \dots, x_m) is chosen such that $f(\xi_m)$ is less than any values of $f(x_i)$, $1 \leq i \leq m$. Then, $f(\xi_m)$ tends to the minimum of f on A and the error on f decreases at the rate of a geometric progression. Similarly, the volume of A_m decreases exponentially. This is known as the convex geometry due to Grunbaum. It states that every hyperplane passing through ξ_m divides A into two parts such that the volume of each of these parts is less than the fraction $1 - (1/e)$ of the volume of convex body A [45].

Last but not least, the method of circumscribed ellipsoids of Numirovski-Yudin-Shor was formulated based on the geometric of an ellipsoid. The method of circumscribed ellipsoids states that half ellipsoid is an ellipsoid of smaller volume than the initial ellipsoid [69, 70]. To make reference, let an ellipsoid circumscribed about A as E_0 and its centre as c_0 . If c_0 lies outside A then the half space does not contain any points of A . Thus, the half of the ellipsoid that does not interact with A can be eliminated. However, if $c_0 \in A$, then $f'(c_0)$ can be computed by method of central section which results in E_0' . Then, the minimisation of the convex functions is obtained by circumscribing about the E_0' . Although the method of circumscribed ellipsoid has inferior rate of convergence compared to the method of central section, it eliminate the need for finding centres of gravity of polyhedrons [41].

Thus, from the three outlined convex optimisation methods the general form of the convex optimisation problem can be reduced to algorithm 1.

Algorithm 1 convex optimisation

Require: $\theta a + (1 - \theta)b \in C$

Ensure: $\theta \in [0, 1]$

$$h \leftarrow f_o(\mathbf{x})$$

$$\min f_0(\mathbf{x})$$

subject to

$$f_i(\mathbf{x}) \leq b_i$$

$$g_i(\mathbf{x}) = a_i$$

Where the vector $x = x_1, \dots, x_n$ is the optimisation variable of the problem and the

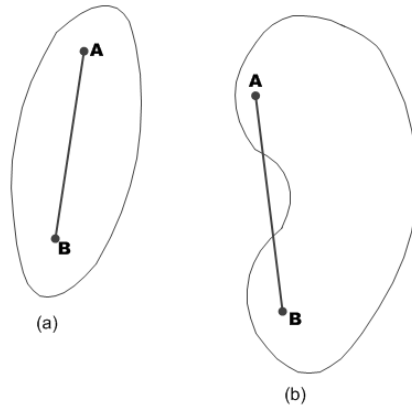


Figure 4.1: (a) Convex set and (b) nonconvex set

function $f_0 : \mathbb{R}^n \rightarrow \mathbb{R}$ is the objective function. The functions $f_i : \mathbb{R}^n \rightarrow \mathbb{R}$ for $i = 1, \dots, m$ are the inequality constraint functions. In addition, constants $b_i = b_1, \dots, b_m$ are the bounds for the constraints. Furthermore, equality constraints $g_i(x)$ and its bounds a_i may be included. Thus, a vector x^* is an optimal solution of the problem $\{\min f_0(x)\}$, if it has the smallest objective value among all vectors that satisfy the constraints. This is true for any z with $f_1(z) \leq b_1, \dots, f_m(z) \leq b_m$ and $f_0(z) \geq f_0(x^*)$.

Convex optimisation is only applicable for convex function or sets. Thus, a set is defined to be convex if and only if any two elements a and b within a set can be joint together by a straight line as demonstrated in Figure 4.1. Mathematically, a set C is convex if $\theta a + (1 - \theta)b \in C$ holds for $\theta \in [0, 1]$. Convex optimisation is a prominent solution because it guarantees strong duality and global optimality for submodular set functions. Transport problems are discrete in nature. Moreover, the closing time of rail-road level crossings catering for heterogeneous traffic planning exhibits submodularity and supermodularity properties. The convex optimisation's effectiveness and fast computation make it ideal to apply in the level crossing closing time problem.

4.2 Mathematical Modelling

The train's longitudinal force model is crucial in understanding the heterogeneity and dynamics of the railway traffic at the level crossings. The train force model consists of the traction force denoted by F_t which propels the train in the forward direction. The opposing forces includes the braking force (F_b), resistive force due to the curvature of the

rail (F_c), aerodynamic drag (F_r) and gravity (F_w). According to Newton's second law of motion, the resultant force is expressed by equation 4.11.

$$M \frac{dv}{dt} = \Sigma F = F_t - F_b - F_r - F_c - F_w \quad (4.11)$$

Where:

M - total train's inertial mass,

v - velocity of the train,

F_t - tractive force propelling forward motion,

F_b - braking force,

F_r - resistive force due to the rail contact with the train axles,

F_c - resistance due to curvature of the rail,

F_w - resistive force due to the weight of the train.

The traction force for the commuter train is derived from 3kV overhead wires. However, intercity and freight locomotive derive traction from converting diesel into propulsion energy. According to [76], traction force derived from the one-axle vehicle model can be approximated by equation 4.12.

$$F_t = \mu_t M \frac{dv}{dt} \quad (4.12)$$

Where: μ_t is the tractive force coefficient.

The basic resistance force due to the contact of the train axles and rail is calculated by Davis equation 4.13.

$$F_r = c_o + c_v v + c_a v^2 \quad (4.13)$$

Where: c_o , c_v and c_a are the coefficients. Whereby c_o represents axle to rail rolling friction and c_v represents mechanical resistance from the shaft rotation and transmission chain dominant at the low travel speed [58]. Aerodynamic resistance is represented by coefficient c_a which has greater impact at high travel speed.

The train is subjected to curvature resistance generated from the train's resistance to the curvature of the rail formation. Curvature resistance force is dependent on the track characteristics, as shown in equation 4.14. As a result, the rail wear and tear is caused by the curvature resistance force.

$$F_c = M \frac{D}{1000r} \quad (4.14)$$

Where:

r is the radius of the rail's curvature,

D is a coefficient of the value between 500 to 1200. However, in this study $D = 500$ is adopted.

Force of gravity denoted in equation 4.15, generates weight resistance on a train as it travel on a gradient surface.

$$F_w = Mg \cos \theta \quad (4.15)$$

All trains considered in this study are assumed to use pneumatic braking system thus braking force can be approximated by equation 4.16 in accordance with the model derived in [71].

$$F_b = \sum_{i=1}^n (\mu_s P_{s,i}) \approx \frac{4\mu_d r_m \sum_{i=1}^n a P_{d,i}}{D_o} \quad (4.16)$$

Where: n is the number brake discs,

P_s and P_d are the clamping force on a brake shoe and pad respectively,

r_m is the medium friction radius,

μ_s is the friction coefficient between the brake shoes wheel treads,

μ_d is the friction coefficient between the brake pad wheel discs,

D_o is the wheel diameter.

As a result of the law of conservation of energy, the integral of the braking force over the braking length is equivalent kinetic energy.

$$\int_0^{L_b} \frac{4\mu_d r_m \sum_{i=1}^n a P_{d,i}}{D_o} = \frac{1}{2} (M + m) v^2 \quad (4.17)$$

Where: L_b is the braking distance,

m is the mass of train wheels,

v is the train speed.

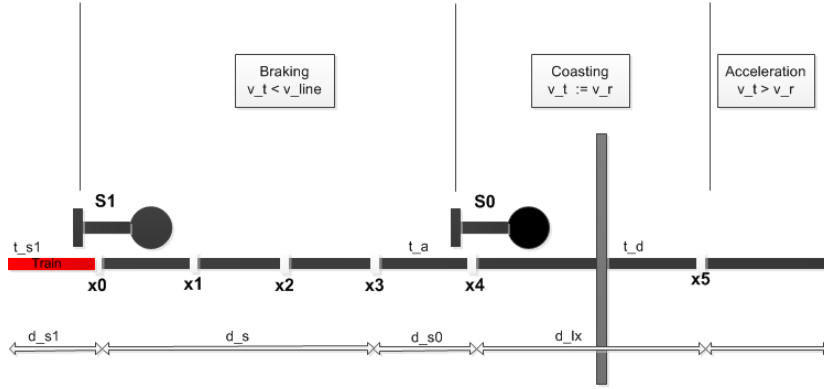


Figure 4.2: Train motion characteristics at the level crossing

Thus, train's braking force can be represented as follows:

$$F_b = \frac{1}{2}(M + m) \frac{dv}{dt} \quad (4.18)$$

To simplify the model, resistance forces are combined to form a net resistive force $R(v, r, \theta)$ which is dependent on the velocity of the train (v), rail curvature radius (r) and the rail gradient (θ). Therefore, equation 4.11 can be re-arranged into

$$M \frac{dv}{dt} = F_t(v) - R(v, r, \theta) - F_b(v) \quad (4.19)$$

The ideal train movement follows a unique pattern at the rail-road level crossings. Hence, Figure 4.2 illustrates the desired train movements as it enters and exits the level crossing. The train can travel at maximum line speed along the network provided that the signalling (signals on green) and rail curvature permits. However, cautious driving is advised on the encounter of the signals displaying yellow as this implies that the next signal is at red. Therefore, at the rail-road level crossing the train must decelerate between $S1$ and $S0$ provided that there are no points machines within the block. This is because the protecting signal ($S0$) only clears when the its approach track (t_a) is occupied. Henceforth, slowing down of the train allows for the train to pass the level crossing at he required speed restriction (v_r). Moreover, the train should ideally be on coasting mode when traversing over the rail-road level crossing area. Finally, the train should accelerate as it exits the deactivation track.

Three modes of train driving are deduced based on the illustrations in Figure 4.2. The train's tractive and braking efforts are controlled by the train driver. Hence, train is on braking mode when $F_b > 0$ and $F_t = 0$. In contrast, the train is in powering (acceleration) mode when $F_b = 0$ and $F_t > 0$. Coasting is achieved when both F_b and F_t are zero. Therefore, train's operational mode can be extended to speed conditions as shown in

Table 4.1.

Table 4.1: Force and velocity conditions for the train's driving modes

Driving mode	Net forces	Velocity
Acceleration	$F_t(v) - R(v, r, \theta) - F_b(v) > 0$	$0 \leq v \leq v_{max}$
Constant speed	$F_t(v) - R(v, r, \theta) - F_b(v) = 0$	$v \geq v_{max}$
Deceleration	$F_t(v) - R(v, r, \theta) - F_b(v) < 0$	$0 \leq v \leq v_{max}$
Stop	$F_t(v) - R(v, r, \theta) - F_b(v) = 0$	$v = 0$

Heterogeneous railway traffic considered in this study comprises of the commuter, intercity and freight trains. Properties of the commuter, intercity and freight trains are listed in Table 4.2, Table 4.3 and Table 4.4, respectively. Commuter trains are mainly reserved for passenger transport services within an urban or metropolitan area. They are characterised by high dispatching rate and frequent stops compared to freight trains. In addition, commuter trains considered in the study uses electric traction of 11kV alternation voltage at 50Hz from overhead wires. However, the intercity and freight trains use diesel-electric traction system because they operate over the longest railway network. Hence, in the case of intercity and freight trainskm traction force is derived from the conversion of diesel to propulsion energy.

Table 4.2: Characteristics of a commuter train

Parameter	Symbol	Value
Train mass	M	45000kg
Train length	L	275m
Speed capacity	v_{max}	120km/h
Acceleration	a_{max}	0.9m/s ²
Deceleration	a_{Dmax}	0.85m/s ²
Max traction	T_{max}	120kN
Max braking	B_{max}	72kN
Friction coefficient	c_o	$1.0 \times 10^{-3} Nkg^{-1}$
Friction coefficient	c_v	$1.0 \times 10^{-3} Ns(mkg)^{-1}$
Friction coefficient	c_a	$2.06 \times 10^{-4} Ns^2(m^2kg)^{-1}$
Traction coefficient	μ_t	0.80

Table 4.3: Characteristics of an intercity train

Parameter	Symbol	Value
Train mass	M	$450000kg$
Train length	L	$375m$
Speed capacity	v_{max}	$100km/h$
Acceleration	a_{max}	$0.8m/s^2$
Deceleration	a_{max}	$0.75m/s^2$
Max traction	T_{max}	$150kN$
Max braking	B_{max}	$86kN$
Friction coefficient	c_o	$5.0 \times 10^{-3} Nkg^{-1}$
Friction coefficient	c_v	$5.0 \times 10^{-3} Ns(mkg)^{-1}$
Friction coefficient	c_a	$1.02 \times 10^{-6} Ns^2(m^2kg)^{-1}$
Traction coefficient	μ_t	0.7

Table 4.4: Characteristics of a freight train

Parameter	Symbol	Value
Train mass	M	$45000000kg$
Locomotive length	L	$450m$
Speed capacity	v_{max}	$75km/h$
Acceleration	a_{max}	$0.8m/s^2$
Deceleration	a_{max}	$0.7m/s^2$
Max traction	T_{max}	$250kN$
Max braking	B_{max}	$150kN$
Friction coefficient	c_o	$7.0 \times 10^{-3} Nkg^{-1}$
Friction coefficient	c_v	$7.0 \times 10^{-3} Ns(mkg)^{-1}$
Friction coefficient	c_a	$2.06 \times 10^{-6} Ns^2(m^2kg)^{-1}$
Traction coefficient	μ_t	0.65

4.3 Level Crossing System

Rail-road level crossing is an open loop control system whereby the controller input is the occupation status of the track sections involved. The occupation status is determined by the axle counter evaluator based on the comparison of the measured induced voltage on the axle counters relative to the threshold voltage. Therefore, the axle counters evaluator is continuously monitoring the induced voltage on the receiver coil of the involved track sections. Thus, the protection system is actuated when the induced voltage on the first

axle counter of the activation track is less than the threshold voltage. This completes the process of securing the rail-road level crossing for the train to pass safely and the controller keeps the state until next change in input. Henceforth, the controller withdraws the protection system when the measured induced voltage on the last axle counter of the deactivation track exceeds the threshold voltage. The explained process in convex set since no other activities can coincide at point in time.

The controller has no capability to ensure minimal level crossing closing time. Moreover, it has no means of distinguishing which type of train is passing over the rail-road level crossing. Therefore, it is ideal to implement the optimisation of the closing time for the rail-road level crossing system at the traffic management layer not at the controller layer. The railway traffic management contains the identification token or number associated with the train, its departure and arrival time and location. Furthermore, the optimiser can be extended to incorporate the property of the trains to be dispatched and their anticipated time spent at each rail-road level crossing system. Lastly, the anticipated time spent at the level crossing and the required driving regime can be made available on cab. Transport planning optimisation problems are discrete. Thus, variables applied are described in subsection 4.3.1 and shall be adopted throughout this chapter.

4.3.1 Variables

Velocity is an integral of acceleration thus in discrete form it is the summation of the product of acceleration intervals and infinitesimal time, as shown in equation 4.20. Similarly, displacement is the integral of velocity, denoted in equation 4.21. The train's acceleration can be represented as a quotient of the net force acting on the train over the total mass in accordance with Using Newton's 2nd law of motion, as shown in equation 4.22. Train's velocity, displacement and time are expressed in equation 4.23, 4.24 and 4.25, respectively. Finally, the train's velocity and travel time are related by equation 4.26.

$$v = \int a dt = \lim_{\Delta t_k \rightarrow 0, M \rightarrow \infty} \sum_{k=1}^M a_k \Delta t_k \quad (4.20)$$

$$s = \int v dt = \lim_{\Delta t_k \rightarrow 0, M \rightarrow \infty} \sum_{k=1}^M v_k \Delta t_k \quad (4.21)$$

$$a_k = \frac{\sum F_k}{M} \quad (4.22)$$

$$v_{k+1} = v_k + a_k(t_{k+1} - t_k) \quad (4.23)$$

$$s_{k+1} = s_k + v_k(t_{k+1} - t_k) \quad (4.24)$$

$$t_{k+1} = t_k + \frac{(s_{k+1} - s_k)}{v_k} \quad (4.25)$$

$$s_k = v_k t_k + \frac{1}{2} a_k t_k^2 \quad (4.26)$$

4.3.2 Solution Formulation

Current rail traffic control system utilise positive train control strategy thus, proposed optimisation method is limited to the positive train control (PTC). The positive train control is a communication based train control which provides trajectory features of trains in the railway network to the traffic operators and other trains within the same network. The PTC has different layers of deployment however it's fundamental principle is bidirectional communication between the central control area, trains and trackside equipment, as shown in Figure 4.3. The railway traffic is operated according to the timetable which is updated in the case of delays. However, train schedule is guided by the railway network's headway. It is imperative to formulate the optimisation solution around the headway since the presence of the level crossing may inadvertently introduce delays in the rail traffic.

As already stated, minimisation of the rail-road level crossing time amid heterogeneous traffic is a convex optimisation problem. In order to solve this problem, the illustrations made in Figure 4.2 and the driving regime defined in Table 4.1 are applied. Hence, the solution is segmented according to the train braking on the approach, coasting through and acceleration on the exit of the rail-road level crossing. Minimising the time spent by the train in each of three defined cruise conditions will yield an optimal rail-road level crossing time. The problem discussed is discrete, thus assuming that t_a in Figure 4.2 has

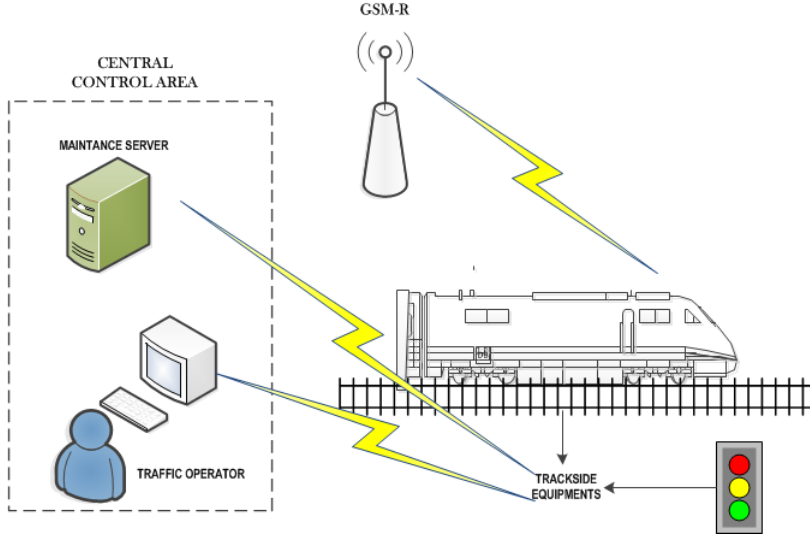


Figure 4.3: Positive Train Control

N increments and t_d increments starts from $N+1$ to M . Therefore, the objective variable t_k at interval k is the time spent by train within the defined segment of the rail-road level crossing. Furthermore, the objective variable t_k is a function of the distance s_k and train's velocity v_k as per equation 4.24 and it is nonnegative.

In the segment where the train enter the activation track, convex optimisation can be posed as shown in 2. This holds if and only if sufficient braking distance can be achieved in this block section. The time spent in this block $t_k^{(1)}$ and the headway time t_h are elements in the convex set C . Thus, $t_k^{(1)}$ is constrained by the resultant force, level crossing speed restrictions and headway time. The resultant force must be less than zero in addition the final train's velocity at the end of the block should not exceed the level crossing speed restriction. Furthermore, $t_k^{(1)}$ should be kept below the headway time t_h to ensure that railway traffic capacity is not affected.

Algorithm 2 Minimisation of the time spent over the activation block

Require: $\theta(t_k^{(1)}) + (1 - \theta)t_h \in C$

Ensure: $\theta \in [0, 1]$

$$t_k^{(1)} \Leftarrow t_{k+1} - t_k$$

$$\mathbf{min} \left\{ \sum_{k=1}^N \frac{2(s_{k+1} - s_k)}{v_k} \right\}$$

subject to

$$F_t(v_k) - R(v_k, r, \theta) - F_b(v_k) \leq 0$$

$$s_k - s_{k-1} \geq s_B \text{ for } k = N$$

$$v_N \leq v_{lx}$$

$$t_k^{(1)} \leq \frac{(N-1)}{M} t_h$$

The algorithm defined in 3 minimises the time spent by trains across the level crossing area $t_k^{(2)}$. However, in this block the resultant force should be zero. The train's velocity must be kept below the imposed speed restriction and the time spent must be a fraction of the headway time. Lastly, the train should accelerate as it exits the deactivation track t_d thus algorithm 4 applies. The minimisation of the time spent on the level crossing exit $t_k^{(3)}$ is subjected to the resultant force greater than zero. Thus, train's velocity is constrained to the maximum line speed and the train must take at least 15% of the headway time. Refer to 4.3.3 for detailed review of the constraints applied.

Algorithm 3 Minimisation the time spent over the level crossing area

Require: $\theta(t_k^{(2)}) + (1 - \theta)t_h \in C$

Ensure: $\theta \in [0, 1]$

$$t_k^{(2)} \Leftarrow t_{k+1} - t_k$$

$$\min\left\{\sum_{k=N+1}^M \frac{2(s_{k+1} - s_k)}{v_k}\right\}$$

subject to

$$F_t(v_k) - R(v_k, r, \theta) - F_b(v_k) = 0$$

$$v_k \leq v_{lx}$$

$$t_k^{(2)} \leq \frac{(N + 1)}{M} t_h$$

The optimal time spent at the rail-road level crossing is the sum of the time spent by the train over the activation and deactivation track as well as the train's exit time. Since, each train type has unique characteristics hence optimisation should be in accordance each train's capabilities. Thus, optimal level crossing given in 4.27 is the sum of the time spent in each of the defined blocks.

$$t_{close} = t_k^{(1)} + t_k^{(2)} + t_k^{(3)} \quad (4.27)$$

Algorithm 4 Minimisation of the exit time from the level crossing

Require: $\theta(t_k^{(3)}) + (1 - \theta)t_h \in C$

Ensure: $\theta \in [0, 1]$

$$t_k^{(3)} \Leftarrow t_{k+1} - t_k$$

$$\min\left\{\sum_{k=N+1}^M \frac{2(s_{k+1} - s_k)}{v_k}\right\}$$

subject to

$$F_t(v_k) - R(v_k, r, \theta) - F_b(v_k) \geq 0$$

$$v_{lx} \geq v_k \leq v_{max}$$

$$t_k^{(3)} \leq 0.15t_h$$

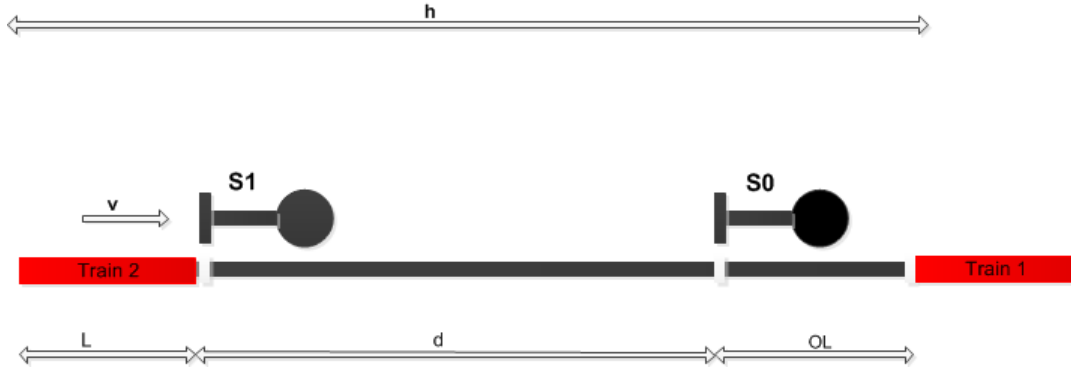


Figure 4.4: Headway time between two trains

4.3.3 Constraints

The rail-road level crossing closing time is constraint by the headway time, speed restriction, minimum and maximum permissible closing time. The time interval between two successive trains travelling in the same direction is referred to headway time and it used as railway traffic capacity measure. Different types of railway headways exist however the one used in the study is derived based on the depiction in Figure 4.4. Thus, headway time is the time at which the second train can depart $S1$ if the first train has passed signal $S0$ and overlap (OL). This assumes that the two trains are the same type and are travelling at the maximum line speed (v) over the headway distance h . Thus, headway time (t_h) is determined by equation 4.28.

$$t_h = \frac{1}{v}(d + L + OL) + t_{aa} \quad (4.28)$$

Where: t_{aa} is the acceleration time and d is the distance between the departure and destination signal.

Furthermore, the train's velocity is constrained by factors such as curvature of the rail, blocked signal, turnout (point machine) and the rail-road level crossing. Therefore, train's velocity profile takes the form presented in equation 4.29.

$$v_t \leq v_{max} = \min\{v_c, v_b, v_p, v_{lx}\} \quad (4.29)$$

Where: v_t is the train's velocity,
 v_{max} is the maximum line speed,
 v_c is the speed limit due to the railway line curvature,

v_b is the speed limit due to the blocked signal,
 v_p is the speed limit due to turnout over the point machine,
 v_{lx} is the speed limit due to the level crossing.

The shortest and longest permissible level crossing closing time depends on the activation point and imposed speed restriction (v_{lx}) due to the level crossing. Activation point is determined by the maximum braking distance of the railway traffic given by equation 4.30. The solution proposed involves heterogeneous railway traffic therefore Table 4.5 lists braking distance of each train type for various speed restrictions. Line speed in this case is $v_{max} = 90km/h$. However, for freight train maximum speed is $v_{max} = 75km/h$ as stipulated in its specifications. Hence, based on the braking distances presented in Table 4.5 the signal $S1$ has to be placed at least 625m away from $S0$ for speed restriction ($0.5v_{max} \leq v$) or ($v \leq 0.33v_{max}$). Moreover, activation point can be 315m from $S0$ provided that the protecting signal has an overlap before the level crossing.

$$s_B = \frac{v_{max}^2 - v_{lx}^2}{2a_d} \quad (4.30)$$

Where:

s_B is the braking distance,

$v_{max} = 32.4m/s$ is the line speed with an exception for the freight train($27m/s$),

v_{lx} is the level crossing speed restriction,

a_d is the train deceleration.

Table 4.5: Braking distance for heterogeneous railway traffic

Train type	$v_{lx} = 0.75v_{max}$	$v_{lx} = 0.5v_{max}$	$v_{lx} = 0.33v_{max}$	$v_{lx} = 0.25v_{max}$
Commuter	270m	463m	549m	579m
Intercity	306m	525m	622m	656m
Freight	228m	391m	464m	488m

4.4 Implementation

The optimisation solution is carried out on Matlab platform using the CVX package for specifying and solving convex programs [77]. Two solution architectures shown in Figure 4.5 and Figure 4.6 are proposed. Architecture presented in Figure 4.5 applies for rail-road level crossings with zero dwell time whereas Figure 4.6 applies for level crossings with nonzero dwell time. The latter is designed for the rail-road level crossings with platform at or in close proximity to the activation point.

The solution for zero dwell time shown in Figure 4.5 begins with monitoring the train upon occupying the approach track $t1$ of signal $S1$ or the track before the activation point depending on the topology. This is followed by command to initiate braking in order to adjust the train's speed to reach the required speed restriction. Convex optimisation is applied to determine the adjust the speed taking into account the imposed level crossing speed restriction, as outlined in algorithm 2.

The rail-road level crossing protection system gets activated upon the occupation of the approach track of the protecting signal $S0$ denoted by $t0$. It is imperative that the train keep to a speed at least $0.8v_{lx}$ in order to ensure minimal level crossing closing time. Therefore, command the train's velocity is adjusted accordingly as it travel past the activation point. This serves as the pre-coasting conditions. Similarly, the rail-road level crossing deactivates the protection system as soon as deactivation track is cleared. The railway traffic will have full control over the rail-road level crossing within the time interval between the activation and deactivation. The algorithm for determining the optimal level crossing closing time (t_{lx}) is outlined in algorithms above.

However, the solution for the rail-road level crossings with nonzero dwell time requires that activation be delayed by the minimum dwell time. This delay is only effective when the train come to a stop at the platform. Minimum dwell time shall be estimated beforehand based on peak times and passenger statistics. In addition, the maximum level crossing closure time is to be extended to $0.75t_h$ in order to accommodate the required deceleration and acceleration time.

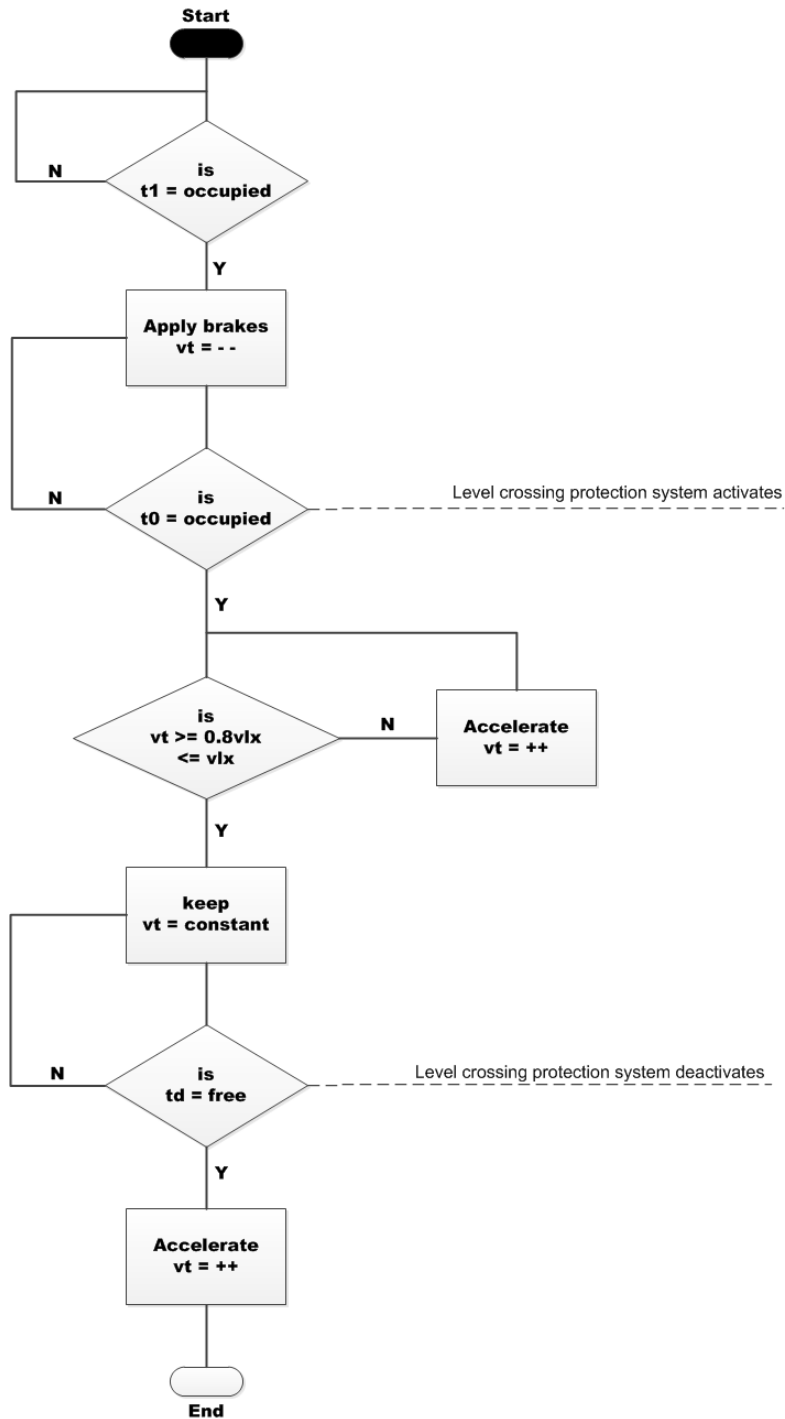


Figure 4.5: Solution architecture for the level crossing zero dwell time

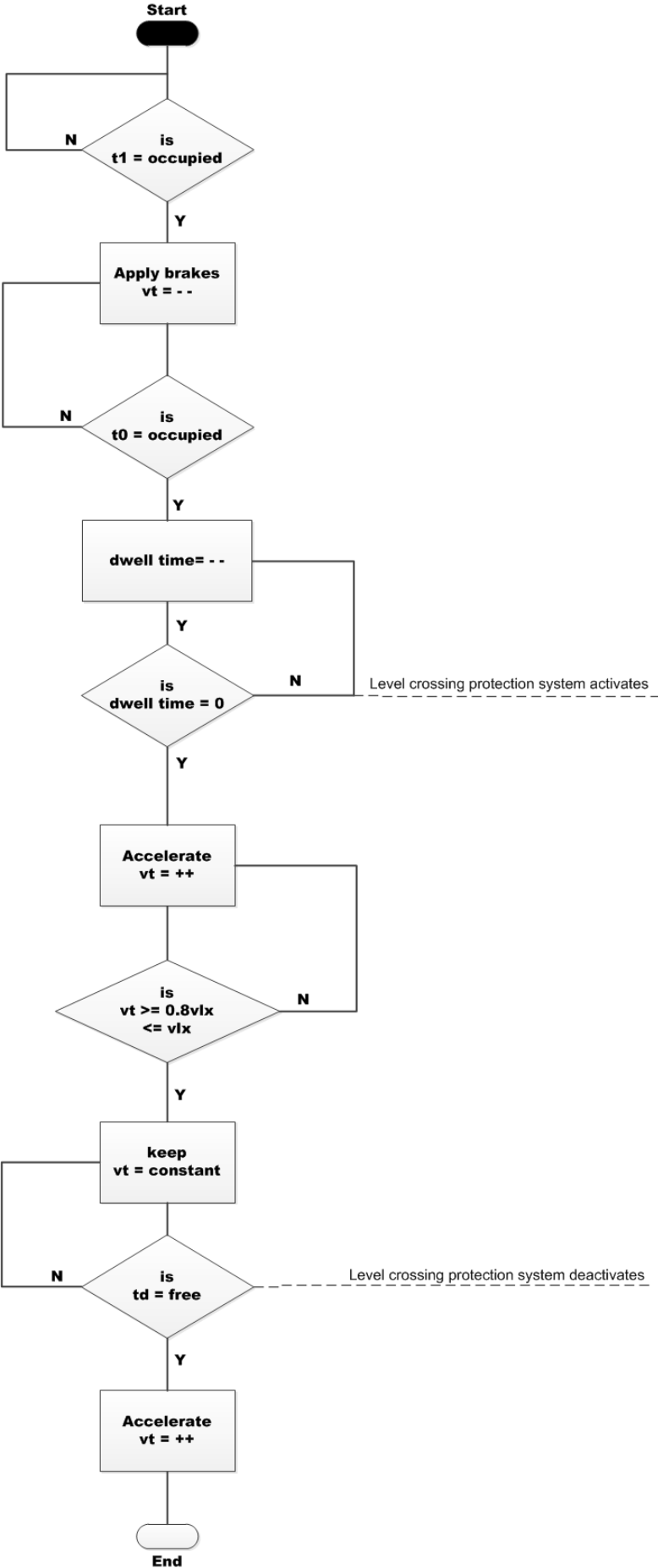


Figure 4.6: Solution architecture for level crossing with nonzero dwell time

4.5 Experimental Results

The convex optimisation algorithm developed has two architectures, one for zero dwell time and the other for nonzero dwell time. Data collected from the level crossings under study is used to train the developed convex optimisation. Thus, the dataset of 6000 samples was collected from the eight level crossings on the southern corridor of the Western Cape metro rail. Furthermore, the data is split into 5000 and 1000 samples for training and testing the algorithm, respectively. First, data analysis is used to extract the model of the features with influence on the level crossing closing time as per findings of 3. The features include dwell time, train's speed and time delay imposed on the protecting signal.

Regression techniques are applied to model the relationship between the dwell time, train's entry, protecting signal's time delay and traffic heterogeneity and the level crossing closing time. Training data of 5000 samples was used to derive the model in python. Dwell time is the occupancy time of the track sections which are part of the station's platform. The train's speed is estimated from the distance-time relation of the activation track. Moreover, time delay imposed on the level crossing's protection signal is inferred from the time at which the approach track was occupied until the signal in question normalises. Linear regression presented less bias and variance hence the parameters of the model are shown in Table 4.6.

Table 4.6: Linear regression model $\{h_\theta(x_i) = \theta_0 + \theta_1 x_i\}$ for $i = 1, 2, 3$.

Feature	θ_0	θ_1	$J(\theta)$
Dwell time	0.992	1.001	0.002
Train's speed	-0.135	-0.036	0.025
Time delay	0.202	0.298	0.024

Since, the level crossing compartment is separated into blocks as per driving regimes outlined above. First, algorithm presented in 2 is applied to determine the minimum closing time at activation block. The time spent at activation is influenced by the dwell time x_1 , train's speed x_2 and time delay imposed on the signal x_3 hence the objective function reduces to 4.31 and the following constraints. Furthermore, the only feature affecting the time spent along and on exit of the deactivation track is the train's speed x_2 . Therefore, objective function algorithm 3 and 4 still hold with v_k changed to x_2 . The

corresponding speed and tractive constraints applies.

$$\begin{aligned} \min \left\{ \sum_{k=1}^N \frac{2(s_{k+1} - s_k)}{x_2} + x_1 + x_3 \right\} & \quad (4.31) \\ \text{subject to} \left\{ \begin{array}{l} \arg \min(h_\theta(x_1)) \leq t_d \\ \arg \max(h_\theta(x_2)) \geq v_{lx} \\ \arg \min(h_\theta(x_3)) \leq t_i \\ F_t(v_k) - R(v_k, r, \theta) - F_b(v_k) \leq 0 \end{array} \right. \end{aligned}$$

Where:

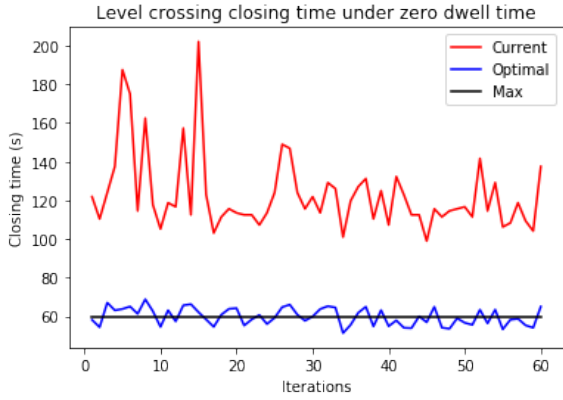
t_d is 10% of the anticipated station's dwell time,

v_{lx} is the level crossing speed restriction assigned to 30km/h,

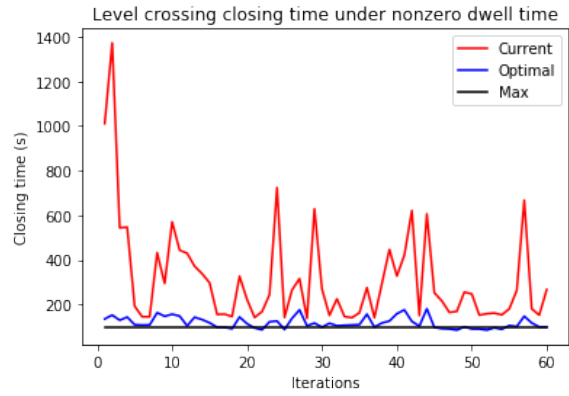
t_i is the time delay on the protecting system which is limited to average driver reaction time 2s.

The results obtained on training the convex algorithm developed are presented in Figure 4.7 and Figure 4.8. The current time spent at the level crossing (level crossing closing time) per train trip and the presented solution results for the zero and nonzero dwell time is shown in Figure 4.7. In addition, cumulative sum of the level crossing closing time was evaluated and results thereof is depicted in Figure 4.8. Thus, performance of the current and convex optimisation solution is measured by the cumulative sum of the level crossing over test iterations. The area bounded by the cumulative sum of the level crossing closing time per test iteration curve and the anticipated permissible closing time is used to compare the performance of the existing and presented solution.

The ratio of cumulative sum of the level crossing closing time per test iteration for optimal and existing solution is evaluated. The ratio is 0.468 for the zero dwell time and 0.375 for the nonzero dwell time is obtained. The obtained ratio of 0.468 implies that convex optimisation can reduce the level crossing closing time by 53.2% for the zero dwell time. Moreover, 0.375 translate to 62.46% closing time reduction for the nonzero dwell time. The optimisation solution show superior performance against the existing solution therefore it is imperative to evaluate its performance relative to the permissible (ideal) closing time. Thus, results presented in Figure 4.7 indicates that optimisation algorithm converges to very close to the maximal permissible closing time. The optimal closing time for the zero dwell time is almost equivalent to required closing time over time. However, the optimal closing time for the nonzero dwell time does not converge to global optima.

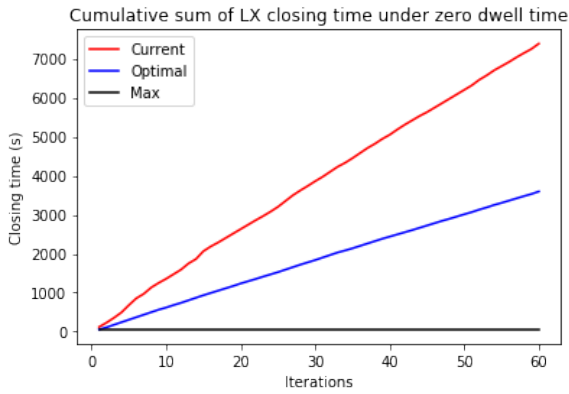


(a) The average closing time for level crossing with zero dwell time

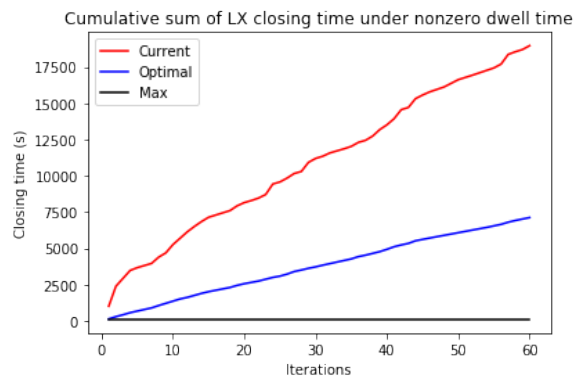


(b) The average closing time for level crossing with nonzero dwell time

Figure 4.7: Level crossing closing time per test iterations



(a) Cumulative sum of closing time for level crossing with zero dwell time



(b) Cumulative sum of closing time for level crossing with nonzero dwell time

Figure 4.8: Cumulative sum of the closing time per test iterations

This is attributed to the approximation of dwell time hence a greedy algorithm can be applied to minimise the perturbations. The actual safety and capacity improvement shall be validated in section 5.

4.6 Conclusion

The convex optimisation solution for the level crossing closing time under heterogeneous railway traffic has been presented. Furthermore, two solution architectures were proposed for the zero and nonzero dwell time. The algorithm is built using a cvx solver which is a Matlab based package for solving disciplined convex programs. Thus, optimal level crossing closing time is attained by optimising the time spent by train entering the activation point, along and on the exit of the deactivation track. The minimal time spent on the defined compartment of the level crossings corresponds train driving regime within these compartment. In addition, the features influencing the level crossing closing time have been applied on the optimisation algorithm. The algorithm showed impressive performance against the existing solution. The cumulative sum of the level crossing closing time over the test iterations indicates that the presented solution reduces the closing time by 53.2% and 62.46% for the zero and nonzero dwell time, respectively. Moreover, the closing time for the zero dwell time converges to maximal permissible closing time. However, the nonzero dwell time have opposite effect thus a greedy algorithm is proposed for estimation of the dwell time.

Chapter 5

Validation

This chapter presents validation of the solution. A brief overview of validation is discussed in section 5.1. The solution presented is aimed at safety and capacity improvement at the level crossings. Thus, validation of safety improvement and capacity improvement are outlined in section 5.2. Concluding remarks are made in section 5.3.

5.1 Introduction

Railway systems are subjected to rigorous validation and verification in accordance with CENELEC standards EN 50126, EN 50128 and EN 50129 [14, 16, 17]. CENELEC EN 50126 details the system's reliability, availability, maintainability and safety (RAMS) requirements and processes [16, 72]. However, EN 50128 are the specifications for certifying software for railway control and protection systems applied in communication and signalling systems [17, 72]. Lastly, EN 50129 are the specifications for the certifying safety related electronic system in railway communication, signalling and processing systems [14, 72]. However, due to time constraints and improvise have been made.

Hence, safety improvement is validated based on the time lost at the rail-road level crossing per train trip. Comparative analysis of the current and presented solution is conducted based on time lost at the level crossing per train trip. Chapter 3 has confirmed that one of the contributors to transit bottlenecks in the railway network is the presence of rail-road level crossings. Thus, traffic capacity refers to critical bottlenecks sections in

a given duration of the train trip [24, 26]. Therefore, capacity consumption is used in validation of the critical bottlenecks due to level crossing.

5.2 Validation: Safety & Capacity

Validation of safety and capacity improvement of the presented solution is detailed in subsection 5.2.1 and 5.2.2, respectively. System and user safety are two different parameters which need to complement each other to ensure overall safety at the rail-road level crossing. Thus, time lost at the rail-road level crossing encompasses both. Capacity is a broad subject but in this case it is limited to traffic bottlenecks in the railway network. Hence, capacity consumption of routes over the level crossings is used validation purpose. Data collected from the eight level crossings under study is used and heterogeneous traffic data is simulated.

5.2.1 Safety

Validation of safety improvement is conducted offline on the recorded level crossing's closing times. The level crossing closing time is equivalent to the time spent by trains at the level crossing. Thus, time spent at the level crossing per train trip is computed for each level crossing under study. Data is populated into a probability density function (pdf). Hence, a pdf of the time spent at the rail-road level crossing per train trip is expressed in equation 5.1 with mean μ and standard deviation σ derived from the dataset. The expected pdf ($g(x)$) is populated from the closing time, taking into account parameters such as dwell time, train's speed and protecting signal's time delay. The expected pdf has mean (μ_e) and standard deviation (σ_e). In addition, threshold closing time takes into account the prevailing constraints; therefore it varies for each rail-road level crossing.

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(x - \mu)^2}{2\sigma^2}\right) \quad (5.1)$$

The expected time spent at the rail-road level crossing ($g(x)$) is given by equation 5.2. Thus, time lost at the rail-road level crossing per train trip is represented by the area R bounded by the threshold rail-road level crossing's closing time, actual and expected pdfs, as shown in Figure 5.2, Figure 5.1 and Figure 5.3.

$$g(x) = \frac{1}{\sqrt{2\pi}\sigma_e} \exp\left(-\frac{(x - \mu_e)^2}{2\sigma_e^2}\right) \quad (5.2)$$

Thus, time lost at the rail-road level crossing is obtained by computing numerical or analytical integration of the functions. The time lost at the level crossing is computed for the existing and presented solution. Therefore, comparative analysis of the time lost at the level crossing under the existing and presented solution is given in 5.2.1.

$$R = \int_{x_i}^{x_t} (f(x) - g(x)) dx =$$

$$= \int_{x_i}^{x_t} \left(\frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(x - \mu)^2}{2\sigma^2}\right) - \frac{1}{\sqrt{2\pi}\sigma_e} \exp\left(-\frac{(x - \mu_e)^2}{2\sigma_e^2}\right) \right) dx$$

Where:

$x_t = T_{threshold}$ which is the maximum permissible closing time,
 x_i is the point of intersection $f(x) = g(x)$.

Results

Safety improvement is assessed using the cross-validation dataset of 1000 samples from the eight level crossings. Thus, probability distribution of the time lost at the level crossing is depicted in Figure 5.1, Figure 5.2 and Figure 5.3. The actual, expected and optimal pdfs of the time lost at the level crossing is indicated in red, blue and green, respectively. The level crossing with maximum permissible closing time of 60s, 100s and 260s are considered.

Thus, it can be noted that distribution of level crossings with expected closing time below 100s (shown in Figure 5.1 and 5.2) are more skewed to the right than those with a higher expected closing time. Therefore, the optimisation is able to perform very well under this conditions thus shifting the distribution more towards the left. However, the optimisation is not as robust for the level crossing with the higher expected closing time (Figure 5.3). This is attributed to the dwell time approximation based on the anticipated value.

It is notable that the presented solution can achieve over 50% reduction in the time lost at the level crossing, as shown in Table 5.1. Furthermore, the effectiveness of the optimisation algorithm is not the same for each level crossing. This suggests that there

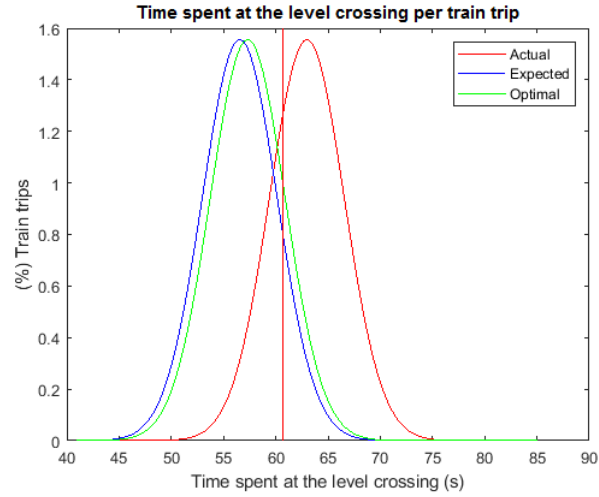


Figure 5.1: Distribution of the time spent at the level crossing $t_{avg} \approx 60s$

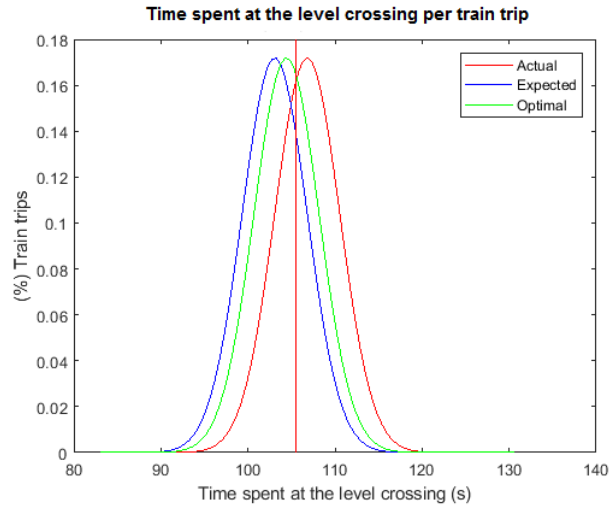


Figure 5.2: Distribution of the time spent at the level crossing $t_{avg} \approx 100s$

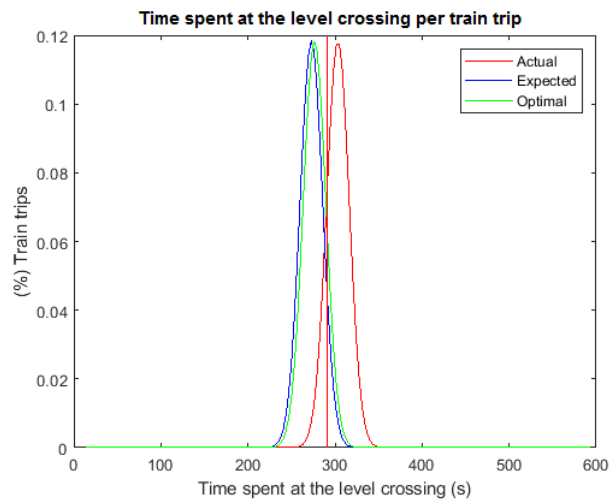


Figure 5.3: Distribution of the time spent at the level crossing $t_{avg} \approx 260s$

may be other features or attributes affecting the closing time other than those considered.

Table 5.1: Time lost at the level crossing: Actual vs Optimal.

Level crossing	Line	$T_{threshold}$ (s)	Actual time lost(%)	Optimal time lost(%)
Albertyn Rd	1	339.7	0.3167	0.0917241
Albertyn Rd	2	335.5	0.36776	0.091724
Austell Rd	1	62.9735	0.4156	0.130112
Austell Rd	2	105.4486	0.3185	0.124916
Kalkbay Rd	1	247.1851	0.4224	0.134877
Kalkbay Rd	2	274.2234	0.5774	0.14215
Military Rd	1	290.8561	0.6367	0.132279
Military Rd	2	97.4201	0.5786	0.133427
Uxbridge Rd	1	74.7672	0.28515	0.134619
Uxbridge Rd	2	60.7218	0.6131	0.134535
White Rd	1	160.1119	0.5364	0.134398
White Rd	2	156.6326	0.6123	0.132985
York Rd	1	206.0263	0.4035	0.134715
York Rd	2	206.9100	0.4044	0.134931

The application of convex optimisation result in the optimal solution indicated in green in Figure 5.1 and Figure 5.2. Thus, presented solution achieves an average time loss between 9% and 14% margins from 30% to 60% on the current solution. Hence, on average the presented solution is validated to reduce the time lost at the level crossing by at least 50%. The cross validation test scored lower than the training data which reported about 62.46% improvement nonetheless the algorithm performs very well.

5.2.2 Capacity

Capacity is measured by the critical bottlenecks due to the rail-road level crossings in the network. Thus, headway time t_h , minimum cycle time (MCT) and capacity consumption (Cap) are used as measures of the capacity improvement. The minimum cycle time refers to the minimum time required to run trains conflict-free in a network [23]. Thus, MCT is calculated for all the level crossings in the corridor and it is the time spent at all level crossing per trip. Similarly, capacity consumption is the ratio between the minimum cycle time and planned cycle time in hourly basis. The headway time is calculated as defined in 4.3.3.

Results

Comparative analysis of the capacity of the level crossing's routes is shown in Table 5.2. The commuter train data is collected from interlocking system whilst the intercity and freight train data is derived from the train driving simulator. Furthermore, traffic capacity is evaluated on 2 hours iterations and the results presented in Table 5.2 are the maximum value for all considered traffic.

Table 5.2: Level crossing capacity analysis.

Time of day	Current solution			Presented solution		
	t_h	MCT	Cap	t_h	MCT	Cap
04:00:00	141.578s	707.801s	0.1966	98.722s	592.32s	0.165
06:00:00	185.560s	1135.627	0.315	118.341s	823.39s	0.230
08:00:00	169.133s	1353.064s	0.376	107.337s	915.083s	0.254
10:00:00	123.545s	803.043s	0.223	99.127s	693.889s	0.192
12:00:00	158.699s	953.194s	0.264	104.875s	734.125s	0.204
14:00:00	111.461s	780.227s	0.216	91.785s	651.192s	0.180
16:00:00	328.129s	2096.903s	0.638	150.065s	981.762s	0.272
18:00:00	208.753s	1610.024s	0.419	116.871s	794.730s	0.221
20:00:00	197.431s	1481.733s	0.412	104.492s	754.118s	0.209
22:00:00	123.957s	619.785s	0.172	85.194s	504.210s	0.140

The presented results indicate that solution provide at least 15% improvement in capacity under normal conditions. Generally, headway time and minimum cycle time are the worst at peak time but the presented solution is able to at least achieve 27% capacity improvement. However, where capacity is severely compromised an improvement of at most 58% can be attained. Furthermore, the current level crossing solution has an average 0.3 capacity consumption at peak time compared to 0.2 on the presented solution. This indicate the fraction of an hour allocated per each train trip in the same line and direction. Thus, current solution allows at most 3 trains to be dispatched travelling in the same line and direction on an hourly basis. Yet, the presented solution is able to accomodate 5 trains on an hourly basis. Thus, an additional 40% dispatch rate is regained. The improvement in capacity implies that the train travel time is reduced. Furthermore, the capacity regained can be distributed to the road traffic thus increasing the opening time of the level crossing. Lastly, the results presented reflects the heterogeneous railway traffic hence better performance is expected for homogeneous traffic.

5.3 Conclusion

Safety and capacity improvement of the presented solution has been validated. Safety at the rail-road level crossings is often compromised by long closing duration. Therefore, safety is validated by comparative analysis of the time lost at the rail-road level crossings. Current rail-road level crossings system have an average 30% to 60% of time loss compared to 9% to 14% time loss under the presented optimal solution. Overall, the presented solution allows for at most 50% recovery of the time lost at the level crossings. However, the solution is not uniform throughout all level crossings thus suggesting that there could be other features affecting the closing time other than those considered. In addition, capacity is validated by headway time, minimum cycle time and capacity consumption of routes over the level crossings. The presented solution can improve capacity of heterogeneous traffic by at least 15% under normal condition. Moreover, the it has been validated that at most 58% improvement is possible where capacity is severely compromised. Furthermore, the solution has been proven to maintain good capacity at peak times relative to the existing solution.

Chapter 6

Conclusion

This chapter provides a summary of the outcomes, contributions and recommendations of the study. Thus, outcomes of the study are discussed in section 6.1, followed by the research's contributions in section 6.2. Lastly, recommendations and future works are presented in section 6.3.

6.1 Research outcomes

The presented study was aimed at optimising the level crossing closing time in a heterogeneous railway traffic. Hence, optimal closing time was directed towards improving safety and capacity at the rail-road level crossings. The optimisation solution was achieved in several steps. Firstly, data analysis was conducted to determine spatial, temporal and behavioural features with highest influence on the level crossing's safety and capacity. The data used was collected from the eight level crossings found along the southern corridor of the Western Cape metro rail. The identified spatial features were further classified into road-based and rail-based. Thus, rail-based spatial features proved to have greater impact on the closing time than the road-based features. In addition, analysis indicated that the presence of platform at or in close proximity to the activation has the greatest impact above all spatial features. However, the general trend with other spatial features is that their impact on level crossing capacity is likely to be significant under degraded mode of operation.

Furthermore, temporal analysis revealed that irregularities in dwell time have a significant

impact on the level crossing's closing time. Inconsistent passenger flow rate at a specific station or halt result in irregular dwell time. In addition, temporal analysis indicated that trains approaching the level crossing from a scheduled stop take longer to clear the level crossing. Likewise, time delays imposed on protecting signals tend to extend the rail-road level crossing's closing time. The impact on the level crossing safety and capacity is severe when dwell time and time delay on the protecting signal co-exist. Lastly, it was shown that manned active level crossing tends to have long average closing time. The cascade of human intervention required to successfully complete level crossing operation results in long closing time.

Conversely, the study has deduced that long waiting time tends to perpetuate unsafe human behaviour at the rail-road level crossing to some degree. Behavioural analysis indicated that systemic processes reinforce compliance particularly within the railway transportation. However, the efficiency of the railway systemic process decreases in a manned active rail-road level crossing. Thus, multiplier effect on the reaction time of the operator and train driver extends the level crossing time. Railway transportation has limited control over road users. Therefore, present study has shown that motorists are most responsive to barrier methods compared to flashing lights. Moreover, cyclists and pedestrians showed reduced responsiveness to both light and barrier warning systems. Yet, completely barricading the rail-road level crossing system reinforces safe behaviour for both pedestrians and cyclists.

Optimal rail-road level crossing closing time was achieved through the application of convex optimisation on the time spent by the train from activation to deactivation point. Thus, convex optimisation technique was formulated based on dwell time, protecting signal's time delay, train speed, train's traction and braking characteristics. Heterogeneous railway traffic included passenger, intercity and freight trains. Since, train follows at most three driving regimes over the level crossing then optimal closing time is guaranteed if and only if the time spent in each regime is minimised. Therefore, driving regimes involved train braking on the approach of the activation point, coasting over the level crossing area and accelerating on the exit of the deactivation point. Moreover, constraints such as resultant longitudinal force, headway time, speed restrictions, minimum and maximum level closing time were factored in the algorithm.

Two solution architectures were proposed for the rail-road level crossing with zero and non-zero dwell time. The latter solution imposed an additional time delay equivalent to an

estimate of dwell time on the activation of the level crossing. Matlab based CVX packages for solving convex programs was used to implement the solution. The algorithm showed remarkable performance against the existing solution. The results show that algorithm reduced the time lost at the level crossings by 53.2% and 62.46% for zero and nonzero dwell time, respectively. In addition, closing time for the zero dwell time converged to maximal permissible closing time but the nonzero dwell time converges to suboptimas. Thus, a greedy algorithm is recommended for estimation of the dwell time.

Validation methods were presented to check safety and capacity improvement of the presented solution. Thus, safety improvement was validated through comparative analysis of the time lost at the rail-road level crossing. This study has shown that the current rail-road level crossings has 30% to 60% time loss per train trip compared to 9% to 14% time loss on the presented solution. Furthermore, validation show that presented solution can achieve at most 50% recovery of the time lost at the level crossings. In addition, rail-road level crossing capacity has been checked by headway time, minimum cycle time and capacity consumption. The presented solution achieved at least 15% improvement in capacity under normal conditions. However, the results showed capacity improvement of at least 27% at peak times with a potential to reach 58% in case where capacity is severely compromised. Lastly, the presented solution can regain an additional 40% dispatch rate.

6.2 Research Contributions

The present study has made the following contributions:

- The present study has contributed to the existing literature in the field of data analysis and extraction of features with highest impact on the level crossing closing time. Furthermore, the study has bridged the gap in the application of convex optimisation techniques to level crossing safety and capacity problem. Moreover, the study has demonstrated the significance of data centric design, optimisation and validation approaches on system with socio-technical and safety critical duality.
- The study has shown the applicability of convex optimisation in heterogeneous railway traffic. Moreover, feasibility of having rail-road level crossings in a shared railway network has been demonstrated.
- Lastly, this study contributed towards the improvement of positive train control particularly in the area of railway traffic management.

6.3 Future work

A novel optimisation solution for the rail-road level crossing closing time for heterogeneous railway traffic has been presented. The presented solution has proven to reduce the waiting time and increase traffic capacity at the rail-road level crossing however the following improvements can be made:

- The presented solution fall short for the level crossings with non-zero dwell time. The solution imposed delay on the level crossing activation by an estimated dwell time. However, the estimated dwell time is derived from the anticipated passenger volume rather than the actual passenger volume at a time of the day. It is inherently difficult to provide accurate estimate of the dwell time and let alone manage it. Hence, the solution is limited by the inability to accurately estimates dwell time. Thus, future works can be focused on the estimation and management of the dwell time. Current research in dwell time explores monitoring the passenger flow rate at the station's platform and on the train using CCTV cameras. Hence, artificial intelligence techniques can be used to provide an accurate estimate of the dwell time in real time.
- Rail-road level crossing systems like any other safety critical element in railway transportation are limited by operating the system under degraded mode. Thus, degraded mode of operation occurs when the system fails to meet the expected level of services such as failure of the wayside track elements or communication breakdown. The presented solution is limited by degraded mode of operations in a form of loss of train detection of the activation or deactivation track sections, failure on the level crossing's protection or warning system, failure of signals involved in level crossing operation. Hence, inability to detect the train at the activation or deactivation track section will not trigger or withdraw the level crossing's protection system autonomously. As a result, human intervention and potential delays on the rail and road traffic are inevitable. In addition, malfunction of the rail-road level crossing's protection system implies that there is a need for human intervention to ensure safe operation. This introduces additional delay but once the pre-activation conditions for the rail-road level crossing are met the presented solution can still be applied. The failure of the LED cluster on the signals implies that the driver will depart at precautious speed when comfortable to do so. In this case, delay cannot be quantified as it varies per individual driver. Degraded mode differs on the failed element or module involved in the rail-road level crossing operation. Therefore, improvement can be made on devising the safety model for the present solution

under degraded mode of operation in addition failure modes can be identified so that contingency plan can be devised.

- Future work can look into finding the computational architecture or model which allows the solution to be integrated into the railway management system using positive train control in real time. Lastly, the solution can be improved by increasing the database of trains since the present study considered only three types of trains; intercity, passenger and freight train.

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