***Train Driver Automation Strategies to Mitigate Signals Passed At Danger on South African Railways***


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**DECLARATION**

I declare that this research report is my own unaided work. It is submitted to the Degree of Master of Science to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other University.

Signed at Pretoria on the 18th day of April, 2018.

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**ABSTRACT**

Train derailments or collisions have the potential to result in catastrophic loss of life and/or destruction of property. Ever higher demands for train density (i.e. trains per hour for a given section of track) as well as the catastrophic results when accidents do occur have given rise to the development of railway signalling systems as mitigation measures (Rolt, 2009; Theeg & Vlasenko (2009b).

Signals Passed At Danger (SPADs) refers to when a train driver passes a stop signal without authority and is one of the typical causes of such accidents resulting in significant damages reported within Transnet Freight Rail (TFR) in recent years. Studies have shown human train driver error and violation of signals to be a significant cause of SPAD events.

This study investigated the application of train driver automation as a mitigation measure against SPADs within the South African railway environment in general and TFR in particular. The study was qualitative in nature, following a model development methodology and used in-depth, semi-structured interviews with railway signalling engineers for data collection. The primary goal was defined to be the development of a train driver function automation method that could be considered the most appropriate within the TFR operational environment.

The study determined the most appropriate method to be that of having a human driver with technical supervision. In this arrangement, the human driver could remain in his conventional role of driving the train but with a technical supervision system superimposed that automatically intervenes if a train driver exceeds his movement authority (e.g. Automatic Train Protection or ATP). This approach mitigates many of the costs imposed by human failure associated with SPAD events, yet retains the value of human flexibility which is especially useful under abnormal circumstances.

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| | |
|---|---|
| ATP | Automatic Train Protection |
| AWS | Automatic Warning System |
| BSI | British Standards Institute |
| CENELEC | European Committee for Electrotechnical Standardization |
| CP | Current Practice (model) |
| CTC | Centralized Traffic Control |
| DTO | Driverless Train Operation |
| EFFBD | Enhanced Functional Flow Block Diagrams |
| FFBD | Functional Flow Block Diagrams |
| FSO | Fully Signalled Operation |
| HF | Human Factors |
| IDEF0 | Integrated Definition for Functional Modelling |
| ITSR | Independent Transport Safety Regulator |
| NASA | National Aeronautics and Space Administration |
| ONRSR | Office of the National Railway Safety Regulator (Australia) |
| ORR | Office of Rail and Road (Great Britain) |
| PRASA | Passenger Rail Agency of South Africa |
| RSR | Railway Safety Regulator (South Africa) |
| SPAD | Signal Passed At Danger |
| STO | Semi-automated Train Operation |
| SysML | Systems Modelling Language |
| TCO | Train Control Officer |
| TCSE | Transnet Centre for Systems Engineering |
| TFR | Transnet Freight Rail |
| TWS | Track Warrant System |
| UML | Unified Modelling Language |
| UTO | Unmanned Train Operation |
| VDU | Visual Display Unit |

# 1 INTRODUCTION

## 1.1 BACKGROUND

Since the construction of the first railways in South Africa in the 1860’s, the network has grown to a total length of roughly 23 273 route kilometers (Transnet Freight Rail, 2017; The Passenger Rail Agency of South Africa, 2015; Van der Merwe, 2008) and in 2015/16 alone carried 67.74 million train kilometers of railway traffic (passengers as well as freight) from South Africa’s major railway operators (Railway Safety Regulator, 2016). The major railway operators active in South Africa today are Transnet Freight Rail (TFR), Metrorail and Gautrain. Of these, TFR is by far the largest with a network consisting of 20 953 route kilometers (TFR, 2017). The Metrorail network consists of roughly 2 240 route kilometers (PRASA, 2015) while the Gautrain network consists of a mere 80 route kilometers (Railway Gazette, 2008).

Of the 73.2 million train kilometers registered on average annually for the period 2013 to 2016, only 44.3 million (60.5%) represent TFR traffic (refer to Table 1.1) which is illustrative of the fact that the traffic densities (trains per hour) of freight traffic typically carried by TFR, is significantly less than that of passenger carriers like Metrorail and Gautrain. It should also be noted that as Metrorail-owned networks are predominantly limited to the greater metropolitan areas of Pretoria, Johannesburg, Cape Town, Durban, Port Elizabeth and East London, Metrorail trains sometimes utilise the TFR national network and operational control systems (Metrorail, 2007). This arrangement includes the running of the long distance Shoshaloza Meryl passenger trains between Johannesburg, Cape Town and Durban (PRASA, 2013). For this reason, despite the fact that TFR is in the freight transportation business, TFR operations also include passenger traffic, making it a good candidate operator to scrutinize when looking at railway operational methods and issues in the context of the South African railway.

**Table 1.1 South African Train Kilometers (Million) - Per Operator**

| Reporting Period | Transnet Freight Rail (TFR) | Metrorail (PRASA) | Other | Total | TFR % |
|---|---|---|---|---|---|
| 2013/14 | 46.9 | 25.0 | 4.4 | 76.3 | 61.5 |
| 2014/15 | 47.0 | 23.9 | 4.6 | 75.5 | 62.3 |
| 2015/16 | 39.0 | 22.2 | 6.5 | 67.7 | 57.6 |
| **Average:** | **44.3** | **23.7** | **5.2** | **73.2** | **60.5** |

Source: South African Railway Safety Regulator (2015, p. 5); RSR (2016, p. 21)

Railway transportation concentrates large quantities of people or goods on networks between various destinations. Inherent in this method of transportation also lies its great weakness: Train derailments or collisions have the potential to result in catastrophic loss of life and/or destruction of property. Ever higher demands for train density (i.e. trains per hour for a given section of track) as well as the catastrophic results when accidents do occur, have given rise to the development of railway signalling systems as mitigation measures (Rolt, 2009; Theeg & Vlasenko (2009b).

The South African Railway Safety Regulator (RSR) has published the following data on the number of operational incidents as well as the associated cost in treasure and human life for the reporting periods 2013 to 2016 (Table 1.2):

**Table 1.2 Total operational occurances and associated costs**

| Reporting Period | Occurances | Injuries | Fatalities | Costs (ZAR) |
|---|---|---|---|---|
| 2013/14 | 4 587 | 1 498 | 456 | 383 393 522.12 |
| 2014/15 | 4 632 | 1 746 | 473 | 438 732 891.76 |
| 2015/16 | 4 250 | 2 290 | 453 | 587 766 960.84 |

Source: RSR (2016, p. 25, p.34, p. 51)

The data from Table 1.2 demonstrates that operational safety incidents in South Africa, including the number of derailments, level crossing accidents and collisions have significant associated costs. The values indicated in the last column (costs) of Table 1.2 represent the reported direct economic costs connected with operational occurrences on South African railways.

The RSR regulatory framework categorises operational occurrences into twelve categories designated A through L (RSR, 2016). These categories typically include collisions, derailments and level crossing incidents but also include fire, spillage and people or passenger related incidents. The operational safety failure under consideration in this study is that of a Signal Passed at Danger (SPAD), which is defined as an incident where a train passes a signal displaying a stop indication or stop aspect, i.e. a red signal, without authorisation (Independent Transport Safety Regulator, 2011). SPADs are the most serious precursors to railway accidents ascribable to operator error (Kyriakidis, Hirsch & Majumdar, 2012). These failures are assigned to RSR category C, the category dealing with unauthorised movements.

## 1.2 CONTEXT

When considering the 3 year period 2013 to 2016, the average number of SPAD incidents reported on South African railway lines is 102.7 per year (Table 1.3).

**Table 1.3 Total SPAD Incidents – SA, AUS, UK**

| Reporting Period | South Africa (SA) | Australia (AUS) | Great Britain (GB) |
|---|---|---|---|
| 2013/14 | 121 | 180 | 290 |
| 2014/15 | 93 | 205 | 302 |
| 2015/16 | 94 | 205 | 282 |
| **Average:** | **102.7** | **196.7** | **291.3** |

Source: Data for column 2 from RSR (2015, p. 22); RSR (2016, p. 26)
Source: Data for column 3 from Office of the National Rail Safety Regulator (2016, p. 26). Note that Australian data was read from a graph – the numbers may not be exact
Source: Data for column 4 from Office of Rail and Road (2017c)

When compared with Australian and British railway statistics and normalised to train kilometers travelled (Table 1.4), South Africa performed slightly better at 1.4 SPADs per million train kilometers when compared with Australia's 1.5 and much worse than Britain which sits at 0.5 for the same period (Table 1.5). Train kilometers (total number of kilometers travelled by trains) was selected for normalisation because it is commonly available in railway safety reports and of all the published measures of railway capacity (i.e. passenger kilometers for passenger trains or ton kilometers for freight trains) train kilometers includes both passenger and freight traffic and are the most representative of the number of train movement authorizations

**Table 1.4 Total Train Kilometers (Million) – SA, AUS, UK**

| Reporting Period | South Africa (SA) | Australia (AUS) | Great Britain (GB) |
|---|---|---|---|
| 2013/14 | 76.3 | 118.2 | 552.6 |
| 2014/15 | 75.5 | 115.7 | 558.5 |
| 2015/16 | 67.7 | 155.3 | 556.7 |
| **Average:** | **73.2** | **129.7** | **555.9** |

Source: Data for column 2 from RSR (2015, p. 5); RSR (2016, p. 21)

Source: Data for column 3 from ONRSR (2016, p. 14)

Source: Data for column 4 from ORR (2017a); ORR (2017b)

**Table 1.5 SPAD Incidents per million Train Kilometers (Normalised) – SA, AUS, UK**

| Reporting Period | South Africa (SA) | Australia (AUS) | Great Britain (GB) |
|---|---|---|---|
| 2013/14 | 1.6 | 1.5 | 0.5 |
| 2014/15 | 1.2 | 1.8 | 0.5 |
| 2015/16 | 1.4 | 1.3 | 0.5 |
| **Average:** | **1.4** | **1.5** | **0.5** |

Source: This data is based on calculations on data from Table 1.3 and Table 1.4

The data therefore indicates that, although SA can still improve substantially when compared with Great Britain, SPAD counts in SA are not disproportionately high when compared with other first world countries like Australia.

Of the annual average number of SPAD incidents in South Africa, 57.2% are from TFR operations (Table 1.6). As TFR train kilometers on average represent 60.5% of the total registered for South African operators (Table 1.1), TFR can be considered a very representative example of South African railway operations as a whole when studying SPADs.

**Table 1.6 South African SPAD Incidents - Per Operator**

| Reporting Period | Transnet Freight Rail (TFR) | Metrorail (PRASA) | Other | Total | TFR % |
|---|---|---|---|---|---|
| 2014/15 | 51 | 30 | 12 | 93 | 54.8 |
| 2015/16 | 56 | 31 | 7 | 94 | 59.6 |
| **Average:** | **53.5** | **30.5** | **9.5** | **93.5** | **57.2** |

Source: RSR (2015, p. 14); RSR (2016, p. 26)

Note that a report containing the per-operator breakdown of SPAD events was not published by the RSR for reporting period 2013/14.

## 1.3 PROBLEM STATEMENT

Of the top five most costly incidents reported in 2014/15 (RSR, 2015), three were related to train handling and control issues (total associated damages of R93 million) with the most costly incident reported during 2014/15 (RSR, 2015) directly attributed to a SPAD (Maputo train-on-train collision - R56 million). This demonstrates that whilst SPADs are not the most common incidents, the associated damages when they do occur can be quite high, presenting a significant risk.

The Independent Transport Safety Regulator (ITSR) body within the New South Wales Government in Australia, concluded that the causes of SPADs generally include technical deficiencies associated with rolling stock or infrastructure but also driver error and violation (ITSR, 2011). Driver errors and violations typically include unsafe actions by the train crew such as the misreading of signal aspects, disregard for cautionary signals, incorrect braking technique, failure to communicate correctly and a range of external and internal distractions. The ITSR also includes organizational factors, such as poor safety culture, poorly designed procedures and inadequate monitoring or supervision, as contributors to such violations. This study, then, proposes, in the context of the failure of the train driver function, to investigate the application of operator automation as mitigation to SPAD incidents in the South African railway environment. TFR seems to be the most representative operator in the South African railway context as it has the largest network, is located in rural as well as suburban environments, carries both freight and passenger train traffic and shows a SPAD record proportional to that of South Africa as a whole. The study is therefore focussed around TFR specifically.

## 1.4 RESEARCH QUESTION

The primary research question that this study intends to answer is:

What method of train driver function automation would be the most appropriate to mitigate SPADs in TFR railway operations?

## 1.5 RESEARCH OBJECTIVES

The objective of this research project is:

To determine the most appropriate method of train driver function automation to mitigate SPADs in TFR railway operations.

This objective will be achieved by accomplishing the following:

### 1.5.1 Conceptualization of TFR signalling methods and practices

Building a conceptual framework for TFR signalling methods and practices with specific focus on how these are applied to effect train movements. This framework is to form the basis of train driver function models that are representative and practicable within TFR. The accuracy of this framework will be established by being reviewed by an experienced signalling engineer.

### 1.5.2 The definition of a current practice train driver function model

Defining a train driver function model representative of the current practices on the TFR network. This model will be qualitative in nature and describe the method by which a train movement is authorised and effected with special emphasis on the role of the train driver in this process.

### 1.5.3 Definition of a proposed ideal train driver function automation model

Defining a proposed ideal automated train driver model. This model will be qualitative in nature and describe the methods by which a train movement is authorised and effected with special emphasis on the role of the automated train driver in this process.

### 1.5.4 To test if the "proposed ideal" model satisfies the critical research question

Testing the proposition that the proposed ideal model meets the requirements set out by the critical research question. The test will take the form of in-depth, semi-structured interviews with railway signalling engineers who have both TFR and industry subject matter expertise.

## 1.6 SUMMARY OF RESEARCH METHODS

The study followed a qualitative research approach in the form of a modelling exercise based on the model development methodology formulated by Robinson (2004) and utilizing Functional Flow Block Diagrams. Semi-structured interviews were held with experienced signalling engineers who were required to generate models describing what they considered to be the most appropriate method of train driver function automation to mitigate SPADs within the TFR environment.

## 1.7 CONTRIBUTIONS

South Africa specific railway signalling principles and practices are currently not well documented in technical literature such as engineering manuals. This study will contribute to the body of scientific knowledge by means of the conceptualization and modelling of how train movements are authorized and effected within the South African railway signalling environment.

## 1.8 LIMITATIONS

The study problem statement does not claim that train driver errors are the only or even the main cause of SPADs nor that train driver function automation is the only or the best mitigation against SPADs but that this specific mitigation method is the subject of this study.

## 1.9 STRUCTURE OF THE REPORT

The research report is structured as follows:

- **Chapter 1 (Introduction)**
  In chapter 1 an introduction to the research project or study is presented. It includes some background on the railway environment in South Africa, the problem to be investigated, the research question and hypothesis, study rationale and project limitations.

- **Chapter 2 (Literature Review)**
  In chapter 2 the literature relevant to the research project is reviewed. It includes an introduction to railway signalling concepts and practices, Human Factors research into the causes of SPADs, SPAD risk management strategies, train driver automation frameworks and the fundamental challenges presented to train driver automation. The chapter concludes with a discussion and listing of features that should be included in the proposed train driver function automation model.

- **Chapter 3 (Research Project Methodology)**
  In chapter 3 the research project objectives and methodology for the study is presented and reviewed. It includes the research approach, measurement and data collection methods, model development as a research method, study validity and reliability as well as ethical considerations during data collection.

- **Chapter 4 (Results)**
  In chapter 4 the results collected in the study are presented. It includes the conceptualization of signalling practices within TFR as well as the data collected during modelling interviews with signalling engineers.

- **Chapter 5 (Analysis)**
  In chapter 5 an analysis is presented of the model data collected in the study and a generic train driver function automation model is proposed than can be considered the most appropriate in the TFR environment. The analysis includes the description and discussion of the commonalities and differences for both the Current Practice and Proposed Automation models as well as a motivation for the final selection of the model.

- **Chapter 6 (Discussion)**
  Chapter 6 will discuss how the project met its defined objectives in an effort to answer the research question. It includes a discussion on how the results compared with the literature, how project objectives were met, if the problem under investigation was solved and if the research question was effectively answered.

- **Chapter 7 (Conclusion and recommendations for further study)**
  In chapter 7 the research conclusions are presented together with some recommendations for further study.

# 2 LITERATURE REVIEW

In this chapter the literature relevant to the research project is reviewed. It includes an introduction to railway signalling concepts and practices, a review of the research into the Human Factors (HF) in the causes of SPADs, SPAD risk management strategies, train driver automation frameworks and the fundamental challenges presented to train driver automation. The chapter concludes with a discussion and listing of features that should be included in the proposed train driver function automation model.

## 2.1 RAILWAY SIGNALLING

This section presents an overview of railway signalling concepts. Railway signalling is the technical discipline specifically responsible for safety in railway movements or the creation of safe capacity. It includes the philosophies, principles and methods used to assure safe and efficient railway movements as well as the systems used to implement these movements.

Pachl (2009) stated there is no international standard relating to how railways are designed, signalled and operated. The modern conception of railways as trains pulled along metal guide rails by powerful mechanical engines, has been around since the early years of the 19th century and every country that has implemented this technology has, in time, developed their own principles and practices. There are three prominent operating philosophies that have influenced the railway operations worldwide:

- British operating principles
- German operating principles
- North American operating principles

In South Africa’s case, the British school of operating principles has been more prominent in railway operations thinking with some influence from German interlocking systems The recent introduction of electronic interlocking systems on South African metro lines has marked a significant shift toward German interlocking philosophy and technology and has in some cases resulted in a temporary confusion in the meanings of certain signal aspects.

To better understand what is required of railway signalling systems it is best to start with the two identifying features of railway systems as presented by Trinckauf (2009):

i. Firstly, that the path taken by a train is determined by the mechanical guidance system of wheel and rail, and this can be changed only at points sets (railway intersections), that trains can only pass each other at specially created crossing locations (at crossing loops for example) and that the paths that trains follow should therefore be predetermined and setup as part of rail traffic control. Due to this reality, including the fact that the railway vehicle (train) and the guidance system (wheel-track and points) are so tightly connected, rail traffic control can be considered a linear control problem.

ii. Secondly, that the relatively poor braking ability or response of steel wheel on steel rail, while maintaining typical line speeds of 50 to 70 km/h, results in a situation where the braking distance for a train typically exceeds the viewing range of the driver. This requires that driver sight on the route should be supplemented by safety systems and precautions to warn the driver in good time about when a speed reduction or a complete train stop may be required on the route ahead.

Such types of technical challenges have led to the development of the discipline of railway signalling and control, including philosophies, processes and technologies.

### 2.1.1 Railway Signalling and Control

The objectives and tasks of signalling and control can be defined as follows (Trinckauf, 2009; Connor, 2017):

| | |
|---|---|
| Operation control system: | The operation control system ensures optimal control of the sequences and processes in the traffic system. |
| Signalling system: | To ensure the safe control of transport processes with the safety aspect stressed. |

The high degree of commonality in the functions and facilitating technologies of these systems has led to them being combined into the signalling systems known today. Modern signalling systems can therefore be considered as systems facilitating operation control while enforcing certain safety precautions. Figure 2.1 is a representation of a modern railway signalling and control system.

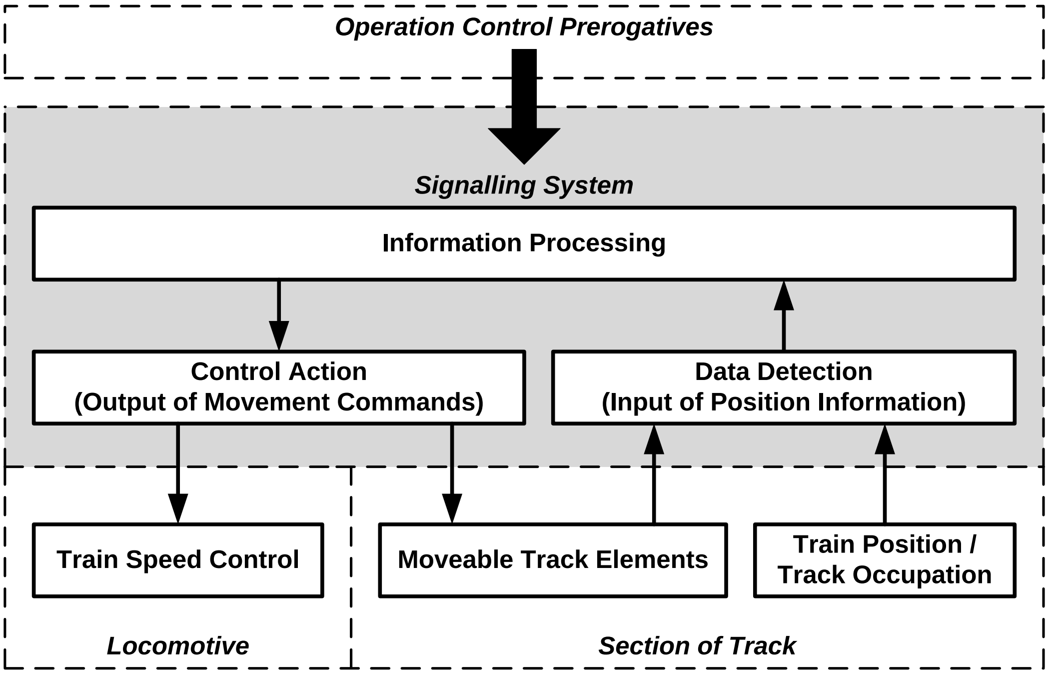


**Figure 2.1 Modern Railway Signalling and Control System**

Source: Adapted from Trinckauf (2009, p. 19)

Operational control objectives are translated into routes, schedules and train movements understandable to the signalling system. Based on a given route definition, the track elements in the route are identified, re-aligned where needed and verified as available and ready for train passage. The train is then given proceed instructions (movement authorities) including speed indications while its passage through the route is tracked. Track elements are typically monitored and controlled by track-side detection devices and actuators. Train movement authorities and speed controls are communicated to the locomotive operator or driver of the train, whose responsibility is to control the train along the route. These authorities can be communicated via track side signalling mechanisms or train-cab based display terminals.

Trinckauf's (2009) *Functional structure of the railway control system* will be used as a basis for the conceptualisation of TFR signalling methods and practices in chapter 4, elaborated on below.

**Field Element Level**

Trinckauf (2009) presents the basic field elements related to signalling systems to include points-sets (or "points"), signals and tracks. More specialized elements do exist but discussion thereof will be considered outside of the scope of this conceptualization.

Points are one of the most basic moveable track elements. The purpose of points is to provide connections between intersecting or crossing tracks (Lykov & Theeg, 2009). The physical structure of points are similar in almost all railways. Essentially they consist of a pair of blade-like objects, appropriately referred to as "points blades", that can be switched to either of two positions (See Figure 2.2).

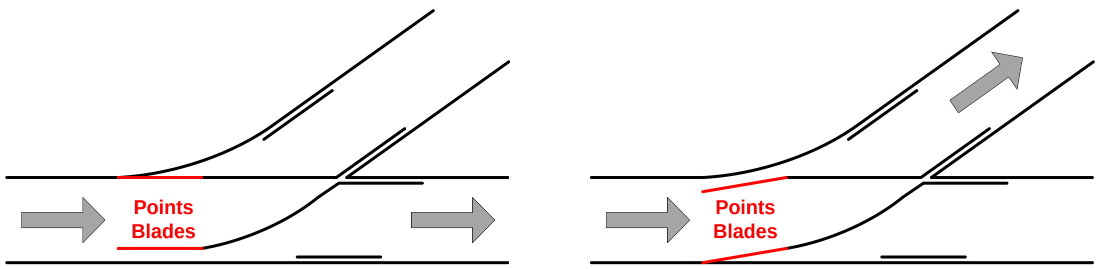


**Figure 2.2 Function of Points Sets**

Source: Adapted from Lykov & Theeg (2009, p. 150)

As indicated in Figure 2.2, points can either lie for the straight, guiding the train to proceed in the straight direction, or for the turn-out, guiding the train to turn off the straight and onto the alternative or turn-out path. Points are typically thrown from one position to the other by means of mechanical, electrical or hydraulic points machines.

The purpose of signals is to convey information and instructions to the train driver (Theeg, 2009). These signals are similar in physical appearance to the traffic lights used to coordinate traffic on road networks. Signals can take many forms, for example man-operated flag movements, track-side mechanical arms or computer displays inside the train cab.

For signalling purposes, the railway line is divided into logical sections (Pachl, 2009) called track sections or simply referred to as “tracks”. These physical tracks are continuously monitored as either being vacant or occupied by railway vehicles. This is used as an indication of the train location or position (Theeg & Vlasenko, 2009a). It should be noted that track detection equipment can technically only verify tracks as being vacant. A “not vacant” status implies that the track is either occupied or that a technical failure has occurred.

**Control Unit Level**

The purpose of element monitoring and control units is to interface field elements to the interlocking and greater signalling system. From here, the components of the field elements are triggered and monitored with regards to their current operating state (Trinckauf, 2009).

**Operations Control Level**

The Train Control Officer (TCO) is the person who initiates the train movement. Although operational planning, time tables and the current operational situation should be taken into account when making their decisions, TCO’s have an element of discretion at their disposal. The ease or effectiveness of this operation would be impacted by the type of system used and the technical generation of information by the system (Trinckauf, 2009).

**Interlocking Level**

The interlocking layer is a safety layer inserted between the TCO on the operations control level and the trains and field elements on the field element layer. The purpose of the interlocking is to transform or filter TCO inputs to exclude unsafe actions like the initiation of conflicting routes, changes to a route while the train is traversing it, or the authorisation of a train to proceed when it is not safe to do so (Trinckauf, 2009; Connor, 2017).

### 2.1.2 Signalling for Railway Operation

Due to the application of steel wheels on steel rails, the braking ability of a train is typically eight times less than for road going vehicles. The resulting extension in braking distance would place a severe restriction on operational speeds (15 to 30 km/h) if train drivers were to space trains based on their viewing range. For regular train movements, procedures of train separation are therefore required that work independently from the viewing range of the driver (Pachl, 2009). The most common train separation methods include Signalled Fixed Block Operation and Cab Signal Operation. Pachl (2009) defines Fixed Block Operation as a system where trains are separated by a fixed block distance. The track is divided into fixed block sections and a given block should be occupied by only one train (Connor, 2017). In a Signalled Fixed Block Operation, access to block sections are limited by signals, which provide movement authority to enter that block section (illustrated in Figure 4.4).

Pachl (2009) and Connor (2017) list the following conditions as having to be fulfilled before a signal can be cleared and a train authorized into a block section:

- The train ahead must have cleared the block section.
- The train ahead must have cleared the safety overlap behind the next signal. Overlaps are discussed later in the paragraph on interlocking principles. Also see Figure 2.4.
- The train ahead must be protected from following train movements by a stop signal.
- The train must be protected against opposing movements.

A Cab Signalled Operation is so called due to the fact that the role of line side signals are fulfilled by a computer terminal located inside the train cab (Pachl, 2009). This form of signalling has many advantages including the improved ability to communicate movement authorities to the driver. Whereas on a line side colour light signalled line, the driver is required to observe the signal in the moment and decode the meaning of the configuration of the signal lamps.  The cab terminal can provide the driver with continuous information on movement authorities, optimal speed profiles and other operational notices. Cab signalling can take many forms - from simple auxiliary systems used to augment existing lineside signals to the more advanced systems where most of the interlocking is train borne, requiring very little line side infrastructure.

Cab signalling technology further enables the method of train separation by “Moving Block” (Pachl, 2009). This is where a virtual block is kept between trains based on the train’s actual braking characteristics (illustrated in Figure 2.3).

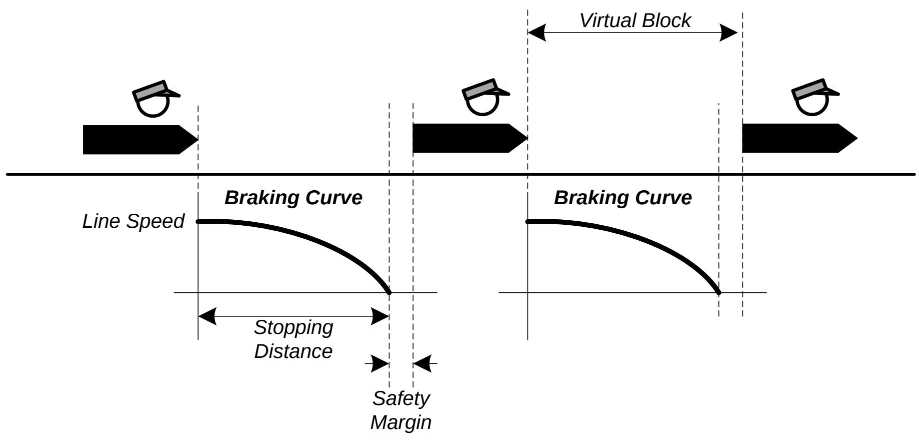


**Figure 2.3 Moving Block Operation**

Some railway lines with a very low density of traffic are operated without any signalling system. This is sometimes referred to as “dark territory signalling” (Pachl, 2009). The movement authorities are issued to the train drivers by the TCO in verbal form using radio or telephone. The authority only takes effect after it has been repeated and thereby verified by the TCO. It is the responsibility of train crews to give information to the TCO about the actual location of the train at certain intervals (Pachl, 2009).

On un-signalled lines, operational control can also be governed by a Track Warrant System (TWS). Trains may occupy tracks only on the basis of the possession of a ‘track warrant’ covering a precisely defined track segment of a given length (Pachl, 2009). The limit of movement authority may be any point designated in the track warrant, but is often designated at the next meeting point. In the most simple of such systems, the TCO relies completely on a handwritten train sheet but in more advanced systems the TCO enters a movement authority into a computer based control system before issuance to the driver. The control system evaluates the entry and rejects any overlapping or conflicting authorities, protecting the TCO from issuing potentially unsafe movement authorities (Pachl, 2009).

**Signals and Signal Aspects**

The application and interpretation of traffic signals are very specific to the country and railway in which they are implemented. TFR specific signals will be discussed in detail in chapter 4.

**Interlocking Principles**

Interlocking is the central function that ensures trains move safely in technical terms. To achieve this, the interlocking obtains information about track occupation by railway vehicles and the position of moveable track elements (refer to Figure 2.1). It then evaluates this information and permits movements via the signals.

The process of using interlocking systems in the application of protected train paths can be described as the definition of “Protected routes & Overlaps”.

Routes are logically defined as from a given signal (departure signal) to the next signal in the same direction or destination signal (Theeg et al., 2009), illustrated in Figure 2.4. The route is then augmented by a relatively short section of track on the other side of the destination signal called an overlap (Theeg et al., 2009; Connor, 2017). This overlap acts as a form of safety margin for when the train driver, due to small misjudgements, might overshoot the stop signal. The typical length of an overlap is much less than the braking distance of a train and is not intended to allow a train to only start braking at the destination stop signal. Routes can be extended by adding any number of follow-on routes although they always terminate in an overlap (refer to Figure 2.4).

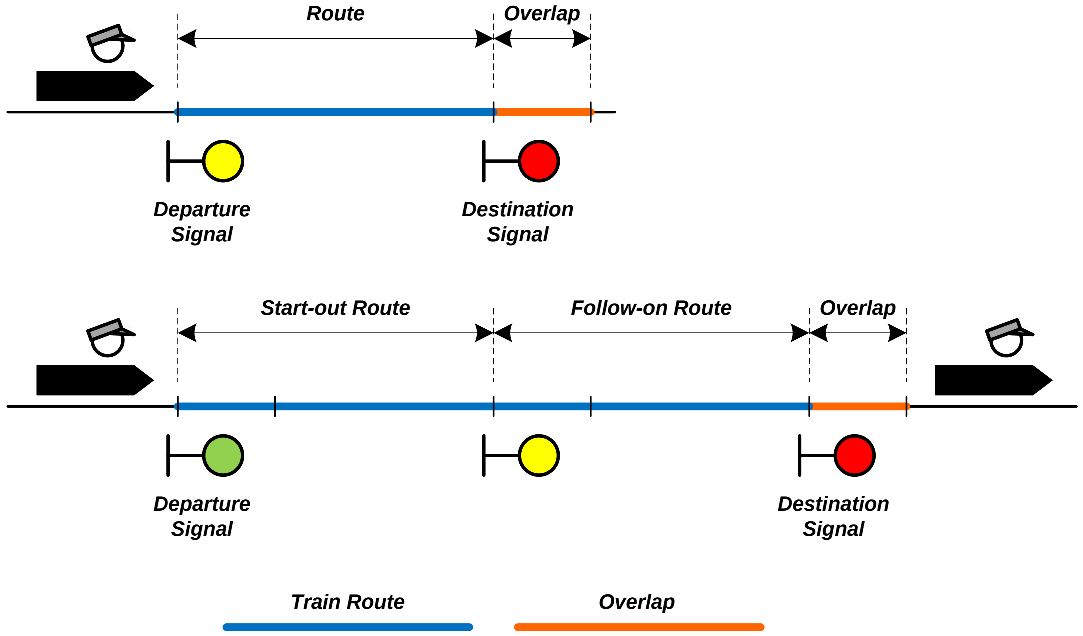


**Figure 2.4 Routes and Overlaps**

Source: Adapted from Theeg et al. (2009, p. 68)

Theeg et al. (2009) presents the typical safety functions performed by the signalling system for the protected route and overlap as:

- Prevention of a derailment on non-continuous guideway locations. Note that moveable track elements have to be in their proper position.

- Prevention of a derailment on the continuous guideway by choice of the proper speed according to the line geometry and the radii at divergences.

- Protection from following, opposing and flank movements.

- Protection against human errors such as overruns of Stop signals, also known as SPADs (only applies to ATP and similar systems – not the current practice within TFR).

The process of route setup, maintenance and ultimate release can also be called the lifecycle of a route. Theeg et al. (2009) presents this lifecycle to typically follow the following steps or stages:

i. ***Route calling***
   This is the initial step of a two-step operation performed by the TCO. The route calling command (departure and destination signal-set) is typically entered via a computer terminal located in the Centralised Traffic Control (CTC) office and communicated to the relevant interlocking system via a remote control network.

ii. ***Route checking***
   The interlocking verifies that the route is indeed available and that no conflicting routes have been setup. In the case of the route being unavailable, the route call is ignored.

iii. ***Commanding of moveable track elements***
   All moveable track elements (for example points-sets) are adjusted to conform to the designed route configuration.

iv. ***Route locking***
   All elements forming part of the route are locked into position and reserved until released.

v. ***Checking of the clear or vacant status of the tracks***
   All tracks that form part of the route are verified as being vacant. This includes the overlap track.

*vi.* ***Signal selection and control***

After the route has successfully been initialised, the signal can be cleared (set to proceed) by the TCO. The interlocking determines the appropriate signal aspect to display, depending on the route layout.

*vii.* ***Route supervision***

During the whole time that the route is active and the entry signal cleared, the route is monitored for any changes in condition that affect the safety integrity of the route. Such conditions may include the failure of a signal lamp filament, the breaking in points-blade detection or the detection of a vehicle or obstacle on the track. If such an unsafe condition is detected, the entry signal is immediately put back to Stop.

*viii.* ***Signal returning to Stop***

As the train passes the entry signal, the signal is put back to stop to protect the route and the occupying train from following movements.

*ix.* ***Route release***

As the train traverses the route, the elements behind the train are released and made available for other route calls. This process, as the interlocking elements revert to its default or “available” condition, is also known as route “normalization”.

## 2.2 THE CAUSES OF SPADS

Signals Passed at Danger (SPADs) are defined as incidents where a train passes a signal displaying a stop indication or stop aspect, i.e. a red signal, without authorisation (ITSR, 2011). A report by the Independent

Transport Safety Regulator (ITSR) within the New South Wales Government in Australia, states that the causes of SPADs generally include technical deficiencies associated with rolling stock or infrastructure but also driver error and violation (ITSR, 2011). Driver errors and violations typically include unsafe actions by the train crew, such as the misreading of signal aspects, disregarding of cautionary signals, incorrect braking technique, failure to communicate correctly and a range of external and internal distractions. The ITSR also include organizational factors that contribute to violations, such as poor safety culture, poorly designed procedures and inadequate monitoring or supervision of train drivers and train control officers (ITSR, 2011).

Driver distraction and errors in sustained attention, has been identified as leading causes of driver error related SPADs (Edkins & Pollock, 1997; Naweed, 2013a; Naweed, 2013b). These errors typically fall into both the categories of commission (inattentive driver going through a stop signal for example) and omission (late application of the brakes for example). These distractions can manifest from internal or external sources and can be task related or unrelated. Naweed (2013a, 2013b) listed the primary factors driving the risk for SPADs in order of importance as:

1. **Time-keeping pressure**
   Time pressure has proven to be the dominating factor in driver error SPAD risk. The goals of keeping time and driving safely can be considered conflicting or pulling against each other. Driving carefully and safely when the drivers know they are behind schedule tends to generate an internal distraction that leads to the loss of focus on their route knowledge such as a signal around the next bend and the anticipated aspect of the signal.

2. **Station dwelling**

   In this scenario the driver pulls away from the station platform as soon as the doors are closed and the staff announce that the train is ready to leave but they do this without a signal to proceed. Time pressure can be an exacerbating factor.

3. **Sighting restrictions**

   These scenarios represent the misreading of a signal and are typically primed or exacerbated by time pressure or delays during station dwelling. A driver of a train on one of two parallel lines would, for example, read the aspect from the signal of the adjacent line instead of his own.

## 2.3 STRATEGIES AND COUNTERMEASURES IN SPAD RISK MANAGEMENT

In their discussion on the requirements, classification and conditions for the application of train protection and control systems, Theeg & Vlasenko (2009) describe their functions as falling into three categories:

- **Cab signalling functions**

  These functions constitute driver warnings and information displays located in the train cab and typically include audible signal warnings, visual repetition of track side signals and dynamic speed information.

- **Supervision functions**

  These functions constitute the monitoring of train conditions and driver behaviour that typically include checks in driver ability, attentiveness and compliance with speed limits.

- **Intervention functions**
  These functions constitute automatic interventions that typically include forced-response driver warnings, disabling of traction power and the application of train service or emergency brakes, to slow the train or bring it to a complete standstill.

Theeg & Vlasenko (2009) classify the particular train protection systems applied within railways into broad categories based on their functions and types of transmission. These systems are reviewed quite comprehensively in their chapter on Train Protection (Theeg & Vlasenko, 2009) but such a review falls outside of the scope of this study.

Naweed et al. (2015) defined the two general categories of formal countermeasures and informal strategies to mitigate SPAD risk in train driving. Formal countermeasures typically include forced-response devices that promote driver awareness to SPAD risk (Automatic Warning System or AWS for example) as well as automatic intervention systems (Automatic Train Protection or ATP for example).

Informal strategies focus on the driver's intention to drive safely. These strategies are created by the drivers themselves to aid them in safely executing their duties – an exercise that can in and of itself be considered safety awareness or safety culture. According to Naweed et al. (2015), these strategies became more important as systems like the AWS and ATP which increasingly not used as intended. Some drivers reported that they sometimes turn down the volume of the AWS system, considering it a distraction, even though such an action was against policy. Others reported using the ATP system as a general method of monitoring speed and not as a safety warning device.

The strategies identified were grouped as specifically applying to the context of service delivery or the context of the driver-signal dynamic:

- **Assessment strategies**
  Two strategies identified in this category are focused on the driver's own assessment of the train he is driving and the driver monitoring of his own fitness to drive safely (Naweed et al., 2015). The first entails the personal assessment by the driver of the state of the train he is driving. This would include knowledge of potential mechanical issues such as braking dynamics that may affect train handling.  The second strategy entails the driver's honest self-monitoring of his levels of emotional distraction and fatigue and reporting concerns about his fitness to drive prior to starting his shift.

- **Task-prioritization strategies**
  Task prioritization strategies include the conscious decision to focus on tasks considered imperative to safe driving and dismiss competing tasks (Naweed et al., 2015).  A typical example would be ignoring an incoming call from the controller whilst navigating a difficult section in the route. When confronted with time table pressure, experienced drivers would consciously prioritize safety.

- **Automatic-attention strategies**
  These strategies are built around cognitive processes and awareness strategies to assist divers in automatically registering signals and changes in signals (Naweed et al., 2015). A typical example would be when a driver observed a signal switching from clear to caution, and that driver would then "turn on a switch" (Naweed et al., 2015, p. 890) in his head helping him to focus on

the signal state and changes in that state. This becomes that much more important in demanding situations.

- **Behavioural strategies**
  These strategies include token actions that drivers devised as aids to help them overcome sighting restrictions, retain signal awareness and act as reminders during station dwells (Naweed et al., 2015). Such actions include consciously setting the direction switch to the neutral position during station dwells, or physically standing up in the cab when a caution signal is encountered.

To apply operator automation as mitigation in SPAD incidents in a South African railway context, this research will examine the following areas of literature pertaining to train driver automation

## 2.4 TRAIN DRIVER AUTOMATION – A THEORETICAL FRAMEWORK

In their discussion on the automation of train operation, Theeg & Vlasenko (2009b) present a framework for train driver automation based on discrete steps or levels of increased automation. For reference purposes, these levels have been numbered from the least amount of automation to the most.

**Level 0** **Manual driving without any automation**
The driver is fully responsible for driving and there is no train protection system present.

**Level 1** **Manual driving with technical supervision**
A Train protection system supervising the driver and enforcing safety in case of driver error.

**Level 2** **Partially automatic operation**

Train driving tasks and responsibilities are divided between the train protection system and the driver. The train protection system is fully responsible for some tasks and the driver is fully responsible for the others.

**Level 3** **Automatic driving with human supervision**

The train is normally driven automatically with the driver observing and intervening in case of danger or technical failure.

**Level 4** **Full automation**

The train is normally driven automatically with no supervision from a human driver. In some cases a person that is normally charged with other responsibilities like ticket collecting, may be available to take control if needed.

Examples of fully automatic driving can be found on some single metro lines in Paris, Lille, Vancouver and Copenhagen as well as on special purpose applications such as airport shuttle trains (Theeg & Vlasenko, 2009b).

Georgescu (2006) has presented the following alternative framework or hierarchy of automated train control:

- **Semi-automated Train Operation (STO)**
  A driver, in the cab, is only responsible for safe departure from stations while the train drives automatically between stations. The driver should also monitor and take control in hazardous situations.

- **Driverless Train Operation (DTO)**
  No driver is required in the cab or to observe. Operational staff may be on board to assist with other tasks such as door closing.

- **Unmanned Train Operation (UTO)**
  No driver or operations staff on board. All functions are performed automatically and supervised remotely.

For the purposes of this study, the framework presented by Theeg & Vlasenko (2009b) is considered preferable because it presents a more linear progression from total manual control to total automatic control whilst elaborating more on the available options within the STO category. UTO, is not directly addressed by Theeg & Vlasenko (2009b), but can be considered a special case within the full automation category.

This framework does not take into account what is referred to as the "proliferation of gadgets" – the simple and unthoughtful addition of a multitude of buttons, sirens, flashing lights and other countermeasures to the train cab. Such measures often prove more disruptive than helpful to the driver in the execution of his duties. This framework presents a simple and theoretically elegant approach to operator automation design in general.

## 2.5 FUNDAMENTAL CHALLENGES TO OPERATOR AUTOMATION

There are fundamental challenges or practical limitations to the concept of operator automation that should also be considered. These include certain ironic circumstances that have to be confronted when considering operator (train driver) automation as well the additional roles that train drivers fulfil above that of train control.

### 2.5.1 The Ironies of Automation

Bainbridge (1983), a seminal author on the topic of operator automation, discusses the ironies faced by the system designer who wants to eliminate the operator from a control system due to his perceived unreliability or inefficiency. Due to the fundamental challenges humans pose to the enterprise of operator automation it is a worthwhile exercise to review Bainbridge's "ironies" more comprehensively below.

Firstly, Bainbridge (1983) considered it ironic that this same designer cannot control the errors that he himself introduces into the design of the automatic control system (designer unreliability). The second irony is that the operator tends to end up with an arbitrary set of tasks that could not be easily or practically automated but that are also not really suited to the abilities of the operator (designer inefficiency). These tasks can generally be reduced to the categories of monitoring of the automatic system for correct operation and the intervention or "taking control" in the case of actual system failure.

**Required knowledge for effective process control**

Bainbridge (1983) suggested that if an operator is required to take control of a process and stabilise it, a certain measure of manual control skill is required. The same goes for fault diagnosis underpinning judgements on process shut down or recovery actions. Such judgements and actions require a certain measure of cognitive skill.

Bainbridge (1983) continued by stating that the manual control skills required to control a complex process can take a long time to master and deteriorate fairly quickly if not practiced regularly. This is evidenced by the fact that experienced operators tend to make step changes or transitions more smoothly, quickly and with fewer actions than less experienced operators. More experienced operators tend to demonstrate an insight or intuition into what the effects of their actions will be. Contrary to this, inexperienced operators rely more on feedback and correction – a process that can be slow and result in a lot of oscillation or “back and forth” action. At the same time it will be more difficult for an inexperienced operator to be able to judge if the feedback received is the result of poor driving or system failure and if system failure has been diagnosed, it may require a very skilled operator to take over to cope without relying on the system. Train driving can be considered a good example of such a complex process. The driver has to adjust and control the speed of the train – a vehicle that has a lot of inertia and is therefore relatively unresponsive to his control actions. At the same time, the driver has to adjust for changing speed restrictions, keep to a strict time table, drive economically and avoid hazards.

Bainbridge (1983) continued by stating that the cognitive skills required, can be categorized into categories of “long-term knowledge” and “working storage”. Long-term knowledge represents the methods and strategies developed over time, while engaged in the control of a process. These methods and strategies are developed during the long run performance of control actions, considering the feedback and retaining what works and works well while rejecting those methods that work less well or not well at all. Unfortunately, this knowledge cannot be acquired without practice and deteriorates if not practiced. Work storage represents knowledge about the current state and behaviour of the process on a given day. This knowledge is similar to adjusting to the look, feel and responsiveness of a rental car you have not driven before where it takes one a few minutes of driving to master its dynamics. A train driver may have to adjust to driving a different kind of train or a train with a different makeup affecting the handling. There may be workmen on the track this week or line of sight may be affected by the weather resulting in the driver adjusting his approach to driving. This kind of knowledge will not be available to the operator when control has to be taken in the moment of need.

**Monitoring and operator attitudes**

Bainbridge (1983) also suggests that before relegating the role of the operator to that of only monitoring an automated process, it should be remembered that the operator was to be replaced by the automatic system because he was perceived to be inferior at the control task to that very automatic system. Now the operator will be required to only monitor and judge if the automatic system is working effectively. The irony of the situation is again evident when considering the monitor has to remain vigilant for an abnormality or failure event that rarely occurs. Owing to the fact that human operators are not always competent at this, they tend to rely on the alarm system to highlight abnormalities. This prompts us to ask: Is the alarm system working correctly and how should the monitor detect alarm system failure? This seems to be an impossible task.

It is also important to consider the impact the job of monitoring has on the operator's attitude. It can easily seem like a job requiring very little skill but a lot of responsibility. It has been shown that such circumstances are conducive to low job satisfaction, high stress, poor health and can also lead to increased error rates.

**Solutions and recommendations**

As is evidenced by the examples above, the problems associated with operator automation can seem like a paradox as the only way to properly automate a process would require the human operator to remain in control. Despite the difficulty, Bainbridge (1983) did attempt to make some recommendations for designers of automatic control systems. These included the use of realistic simulators or manual driving periods to keep the operator's driving skills in practice and other information interfaces that may help the monitor to evaluate the decision making process as executed by the automatic system.

It is significant to discover find that a more recent review of Bainbridge (1983) by Rooksby et al. (2012) has found that examples of these ironies are still prevalent and that such fundamental ironies can be expected to persist for some time to come.

### 2.5.2 Hidden roles of the Train Driver

In their study on the challenges presented in the full automation of the Helsinki Metro, Karvonen et al. (2011) have made the point that there is more to the train driver than basic train control. The case is presented that when the Helsinki Metro operation is considered as a whole, the driver is responsible for operating the train, taking care of passengers, observing events outside the train and acting positively in exceptional situations.

**Driving the train**

Karvonen et al. (2011) proposed that the driver's position in the train cab provides him with a direct view of the track, stations, platforms and passengers while operating the train. This places him in a unique position to anticipate, observe, interpret and react to events in that environment. Some of these events may require a speedy reaction such as when an obstacle is observed on the track ahead or when intruders or vandals are detected inside the security fence – observations and reactions that may prove difficult if performed from a remote location.

**Passenger care**

Karvonen et al. (2011) also proposed there are certain tasks that are fairly trivial for a human being to perform but that can be extremely difficult for an automatic system to perform. When considering the design of safety critical systems, it should be remembered that computers excel only at repetitive, basic tasks, and not at complex problem solving. A typical example of this limitation is passenger care. Passengers are independent actors whose actions may be unpredictable. A human train driver, therefore has a natural interface with human passengers.

In the case of emergency, be it a medical condition of a passenger, train accident, or a fire, the presence of a human driver on site to calm other passengers, assist with orderly and speedy evacuation and to coordinate with emergency services is incomparable. In general, the train driver can act as the on-site representative of the railway company for passengers, clients or emergency services when the need arises.

**Interactions with other actors of the metro system**

Lastly, Karvonen et al. (2011) proposed that the train driver also acts as an important link with other actors in the metro system such as the traffic controllers, security guards and maintenance personnel. His actions may include reporting of potential hazards, security risks and technical failures. The driver is also near at hand to fix small technical faults such as train door faults that can bring the whole operation to a stand-still if an unmanned model was pursued.

## 2.6 SUMMARY OF KEY CONCEPTS

This section summarises the key concepts for train driver automation that could be gathered from a review of the literature. The concepts will be presented through the different levels of automation, starting with the highest level, and evaluating if it should be eliminated or disqualified as a viable option.

### 2.6.1 Level 4 – Full automation

At first glance, full automation seems to deliver on all of the perceived advantages of train driver automation. These include:

- Increased safety in the mitigation of driver induced SPADs (Naweed et al. (2015).

- Increased cost effectiveness due to reduction in personnel requirements and more efficient driving profiles under computer control (Karvonen et al., 2011).

- Enablement of higher traffic rates and operational flexibility (Karvonen et al., 2011).

Yet, difficulties are soon revealed when the train control function is considered within the greater context of the railway operation, and operating in the real world. This perspective can be considered as the systems level or system engineer’s view. It may not be that difficult to automate train control, but to automate the train driver may not prove as simple. Consider the following:

- When the inevitable technical failure does occur, what fall-back modes and recovery mechanisms can be put in place to maintain safety and not bring the whole operation to a stand-still? In such cases a ready and able human train driver is inevitably required to monitor the system for correct operation and take control when needed (Bainbridge, 1983) like in automation level 3 (automatic driving with human supervision).

- Increased automation may not lead to a reduction in staff. A reduction in train drivers due to automation may only lead to increased requirements in support and supervisory staff and more sophisticated levels of training (Karvonen et al., 2011).

- There are certain functions that may be quite trivial for a human train driver to perform but almost impossible to automate. These include the ability of a human train driver to observe potential hazards and react to those hazards, passenger care under normal and emergency circumstances, debugging of small technical failures such as door problems and a whole range of interactions with operations and maintenance staff (Karvonen et al., 2011).

On the basis of these criticisms, automation Level 4 (full automation) will not be considered.

### 2.6.2 Level 3 – Automatic driving with human supervision

Automatic driving with human supervision effectively counters most of the defects introduced with full automation but it is confronted by another kind of problem – that of having a fully capable human driver at hand to monitor and intervene when necessary. Bainbridge (1983) asserted that:

- The manual control skills and cognitive skills required for train control will soon deteriorate in a driver if not practiced regularly.

- A driver whose responsibility has been relegated to monitoring the driving performance of a machine whose driving skills are perceived to be superior to his own may not be the right person for the job. He may also not have enough insight into the decision making process to judge when things are going wrong and require intervention.

- A driver assigned to monitor an automatic system may very well feel that his job requires little skill, that he has very little insight and control of what is happening, yet is held responsible for the outcomes. These working conditions have shown to lead to high levels of stress and unhappiness and increased error rates.

On the basis of these criticisms, automation Level 3 (automatic driving with human supervision) will not be considered.

### 2.6.3 Level 2 – Partially automatic operation

Level 2 automation does not seem to counter the criticisms of Level 3 (automatic driving with human supervision) and will therefore not be considered.

### 2.6.4 Level 1 – Manual driving with technical supervision

Manual driving with technical supervision seems to be the most practical option for the following reasons:

- The driver is maintained in his traditional role mitigating most of the fundamental criticisms to automatic drivers faced by levels two, three and four.

- In addition, the technical supervision system can be scaled to cover only the functions critical to safety and can therefore be much less sophisticated and less expensive than a fully functional automatic driver.

- Lastly, the technical supervision system can simply be superimposed over the current manual driving model and the implementation will therefore result in minimum disruption to ongoing operations.

## 2.7 RECOMMENDATIONS FOR THE PROPOSED IMPLEMENTATION

The following recommendations for the development of the proposed ideal model emerged from the review of the literature:

Firstly, Level 1 automation (manual driving with technical supervision) is the recommended automation model to be implemented. It should be noted that, to improve the practicability of the new model in the TFR railway environment, the model should be based on the current signalling and operational practices within TFR.

Secondly, the formal countermeasures and informal strategies presented by Naweed et al. (2015) align reasonably well with the two elements of probability and criticality that make up the European Committee for Electrotechnical Standardization (CENELEC) concept of risk (BSI, 1999). The informal strategies and vigilance improvement systems attempt to reduce driver error rates while intervention systems minimise the effects if driver errors were made. Although it is desirable to try and reduce the probability of train driver error, the methods seem to be somewhat open-ended as they cannot enforce safety. It does not mean that such methods are ineffective and should not be investigated or implemented or that intervention systems are not subject to failure (Edkins & Pollock, 1997; Scott & Gibson, 2012 cited in Naweed et al., 2015) but it can be argued that the vigilance improvement systems do not present a solid foundation for safety control (Theeg & Vlasenko, 2009; Kyriakidis, Hirsch & Majumdar, 2012). Reduction in the adverse consequences seems to be the most appropriate and accessible approach in this case as it closes the loop in terms of safety enforcement (the result is forced) and is based on technologies that are well established and well understood. These systems (Automatic Train Protection and others for example) are based on the monitoring of the human driver and enforcing safety by applying the brakes if the driver significantly exceeds the required speed restrictions or movement authorities (Theeg & Vlasenko, 2009). In many ways such an approach constitutes having all of the advantages of a human train driver, which has been shown to be considerable (Bainbridge, 1983; Karvonen et al., 2011), whilst mitigating the disadvantages. It is therefore recommended the new model approach be along similar lines to ATP systems.

Thirdly, it may be worthwhile to consider adding functions that aid the driver in better driving but such functions should not form the basis of safety.

# 3 RESEARCH PROJECT METHODOLOGY

This chapter presents and discusses the research methodology followed in the design and execution of this study. This includes the research approach, objectives and design as well as data collection and analysis methods. A discussion on the validity, reliability and ethics of the study are also included. The chapter concludes with a summary diagram of the resulting research project lifecycle.

## 3.1 RESEARCH APPROACH

This study investigates the human train driver associated causes of SPADs, proposing to develop and present a hypothetical automation model for the train driver function that can effectively mitigate SPADs and that can be considered as the most appropriate within TFR railway operations. The nature of the data to be collected therefore recommended a qualitative research approach.

Qualitative research is interpretative and aims to provide a depth of understanding (Dudovskiy, 2011). Qualitative methods are typically based on words, perceptions and feelings rather than numbers and typically includes experiments, interviews and questionnaires with open-ended questions (Dudovskiy, 2011). Such methods consider real-world phenomena while capturing and studying the complexity of these phenomena (Leedy & Ormrod, 2015). This is in contrast to quantitative research which is presented by Dudovskiy (2011) as describing and measuring the level of occurrences on the basis of numbers and calculations, typically asking questions like How many? or How often?

A qualitative research approach may present several advantages but also present certain challenges. Leedy & Ormrod (2015) present the following typical advantages of a qualitative approach:

- Exploration: It can help you gain initial insights into what has previously been a little-studied topic

- Multifaceted description: It can reveal the complex nature of certain situations, processes, relationships and systems.

- Verification: It can allow you to test the validity of certain assumptions, theories or generalizations within real-world contexts.

- Theory development: It can enable you to develop new concepts or theoretical perspectives related to a phenomenon.

- Problem identification: It can help you uncover key problems, obstacles or enigmas that exist within the phenomenon.

- Evaluation: It can provide a means through which you can judge the effectiveness of particular policies, practices or innovations.

Leedy & Ormrod (2015) also describes some of the disadvantages or challenges introduced by a qualitative research approach:

- That, as a general rule, it does not allow you to conclusively identify cause-and-effect relationships (questions such as “what caused what?” or why such-and-such happened?).

- In cases where the research questions are especially open-ended, it may be difficult to identify the exact methods to be used. For this reason, the researcher may have to adapt his methods as data comes in.

As the purpose of this study was to develop a proposed ideal model of train driver automation that represents an improvement on the current-practice manual driving model and to verify this model as the most appropriate for TFR railway operations, a qualitative research approach was deemed preferable.

## 3.2 RESEARCH OBJECTIVES

The following objectives were defined for this research project:

### 3.2.1 Conceptualization of TFR signalling methods and practices

This objective entailed the building of a conceptual framework of TFR signalling methods and practices, with specific focus on how these are applied to effect train movements. This framework was to form the basis for the creation of train driver function models that are representative of and practicable within TFR. The validity of this framework was established by being reviewed by a signalling engineer with extensive experience within the TFR signalling environment.

### 3.2.2 Establishment of the current practice train driver function model

This objective entailed the establishment of the train driver function model representative of the current practise on the TFR network. This model is qualitative in nature, and describes the method by which a train movement is authorised and effected with special emphasis on the role of the train driver in this process.

### 3.2.3 Definition of a "proposed ideal" train driver function automation model

This objective entailed the definition of a proposed ideal automated train driver model. This model is qualitative in nature, describes the methods by which a train movement is authorised and effected with special emphasis on role of the automated train driver in this process.

### 3.2.4 To test if the proposed ideal model satisfies the critical research question

This objective entailed the testing of the proposition that the proposed ideal model meets the requirements set out by the critical research question. The test took the form of in-depth, semi-structured interviews with railway signalling engineers who have both TFR and industry subject matter expertise.

## 3.3 RESEARCH DESIGN

Saunders et al. (2009) define the research design as the general plan the researcher will follow in order to answer the research question(s). This process can also be described as turning the research question into a research project (Robson, 2002). As the study followed a model development process, the design description for this research project will include pre-modelling conceptualization as well as model development concepts, process and language.

### 3.3.1 Pre-modelling conceptualization

The purpose of pre-modelling conceptualization is to establish an understanding of South African signalling principles, practices and systems. This conceptual framework formed the basis for the proper modelling of train movement authorization. As the researcher is himself a practicing railway signalling engineer, the participant observation method was deemed most appropriate in the development of this framework. Participant observation, as described by Gill & Johnson (2002) as well as Delbridge & Kirkpatrick (1994), is where the researcher attempts to fully participate in the lives of his subjects, becoming part of the group or organization and being immersed in the research setting. Within the spectrum where the researcher's role can vary from full spectator to full participant and the awareness of the subjects being studied (overt or covert study), Gill & Johnson (2002) has defined the following taxonomy (Figure 3.1):

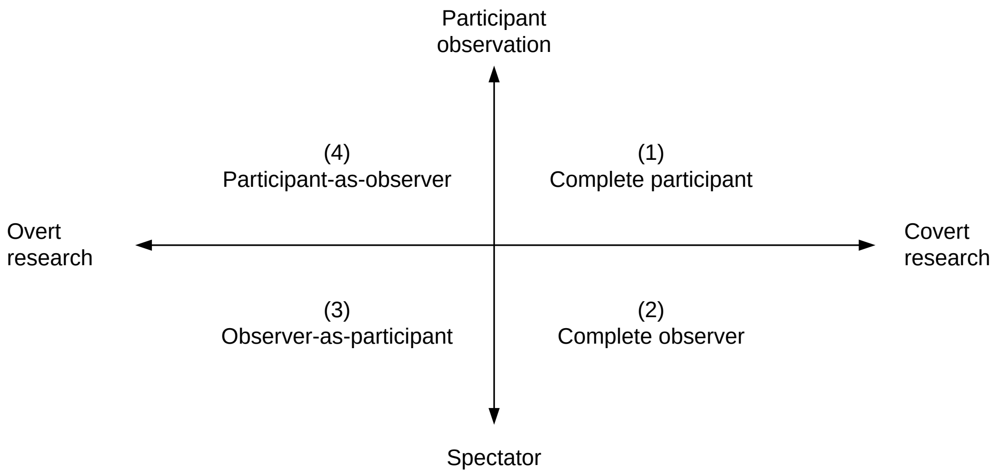


**Figure 3.1 Participant observation role taxonomy**

Source: Gill & Johnson (2002, p. 149)

Within the participant observer spectrum, the participant-as-observer role (quadrant 4, Figure 3.1) was deemed most appropriate and presents several advantages for the study. Firstly, the trust relationship between the researcher and the subjects that is created or exists due to the him being part of the group permits him access to activities (discussions and technical literature for example) that may otherwise have been out of bounds (Punch, 1993). Secondly, the fact that the researcher and the scope of his research is known to the subjects, allows him to ask clarifying questions to enhance his understanding. Lastly, this approach may induce informants to adopt a perspective of analytic reflection on the processes in which they are involved (Robson, 2002).

### 3.3.2 Model development

Buede (2009) defines a model as an incomplete representation of reality (an abstraction) that is typically used to answer one or more specific questions where the answers should provide greater validity or insight than is possible without the model. Many examples of models can be given. For example, a small scale physical model (quantitative) can be used to evaluate the aerodynamics of an aircraft in a wind tunnel. A random number generator (quantitative, mathematical) can be used to evaluate the statistical propensities when flipping a coin. A system requirements specification can be considered a qualitative model of the system's performance and capabilities. These examples can all be categorised as descriptive models, as they seek to predict answers to questions for which the truth may or may not be obtained in the future. Descriptive models are measured by their power or richness of addressing a wide range of problems, understandability and accuracy with which they can be used to define the relevant entity (Buede, 2009).

Quantitative and qualitative models can also be differentiated by the types of answers they can provide.  Quantitative models provide answers that are numerical. For example, How much? How often? How good? Qualitative models provide symbolic, textual or graphic answers typically based on logic, theory or verbal descriptions. For example What needs to be done? How well? By what or by whom? Graphic models typically use simple artistic means to represent a hierarchical structure, the flow of items or data though a system's functions, or the dynamic interaction of a system's components (Buede, 2009).

This study opted for the development of a qualitative model, descriptive of the structure and behaviour of the system by which train movements are and should be authorised and effected within TFR.

### 3.3.3 Model development process

Robinson (2004), while acknowledging that modelling is more of an art form, has presented the following framework for the process of creating a conceptual model:

- Develop an understanding of the problem situation
- Determine the modelling objectives
- Design the conceptual model: inputs and outputs
- Design the conceptual model: the model content

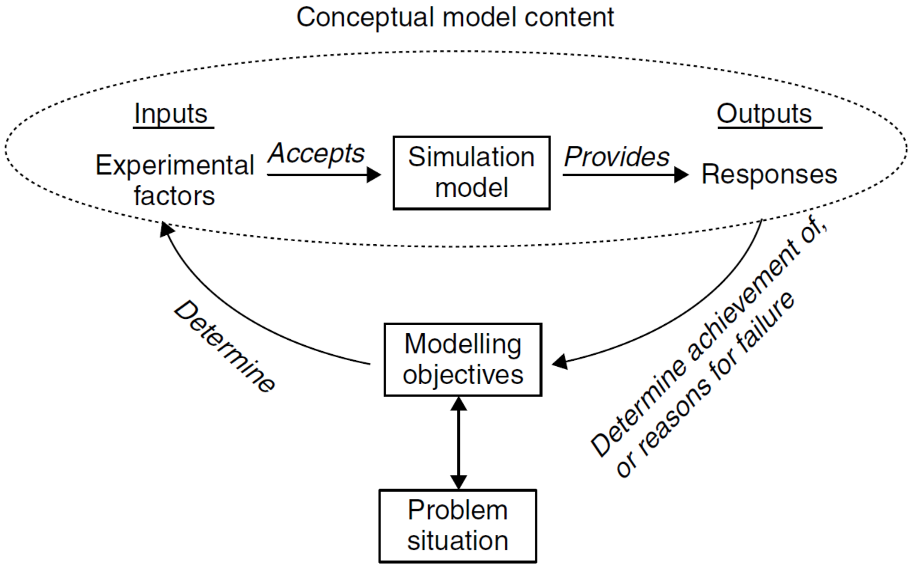


**Figure 3.2 Framework for Conceptual Modelling**

Source: Robinson (2004, p. 78)

The problem situation and modelling objectives for this study were discussed in detail in Chapter 1 (Introduction). The model also does not have inputs and outputs apart from starting with the TCO defining a movement authority resulting in the execution and completion of the subsequent train movement. The design of the automation model content was achieved by forming a concept of TFR signalling practices, followed by interviews with signalling engineers during which examples of current practice and proposed ideal models were generated.

### 3.3.4 Modelling language

A modelling technique also requires a modelling language. Every language has semantics, a set of symbols or signs, which form the basis of representations in that language. In addition to semantics, every language has a syntax that defines proper ways of combining the symbols to form thoughts and concepts (Buede, 2009).

There are a multitude of modelling languages that can be used to represent the kind of models required by this study. Integrated Definition for Functional Modelling (IDEF0), Enhanced Functional Flow Block Diagrams (EFFBD's), Unified Modelling Language (UML) and Systems Modelling Language (SysML) are examples of popular modelling languages used within the systems engineering community. Considering the nature of the models defined in this research, the language selected should at a minimum be able to represent the structure and behaviour of the system (Buede, 2009).

For the representation of system structure, a simple block diagram scheme was employed illustrating the different components and role players within the system and how they relate to one another. Figure 3.3 is an example from Buede (2009) of the structure of an elevator system.

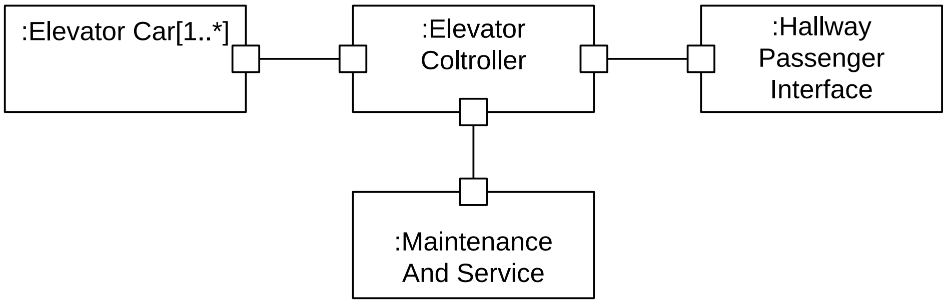


**Figure 3.3 Example of System Structure**

Source: Buede (2009, p. 100)

For the representation of system behaviour, the EFFBD language was selected. Conventional FFBD's are made of functional blocks, each representing a definite, finite, discrete action to be accomplished. The behaviour model is developed using a series of diagrams to show the functional decomposition and to display the functions in their logical, sequential relationship. Diagrams are laid out so that flow direction is generally from left to right. Lines and arrows connecting functions indicate function flow and not lapsed time or intermediate activity. Common logical operations (i.e. concurrency, selection, iteration, repetition and loops) can also be implemented (National Aeronautics and Space Administration, 2007).

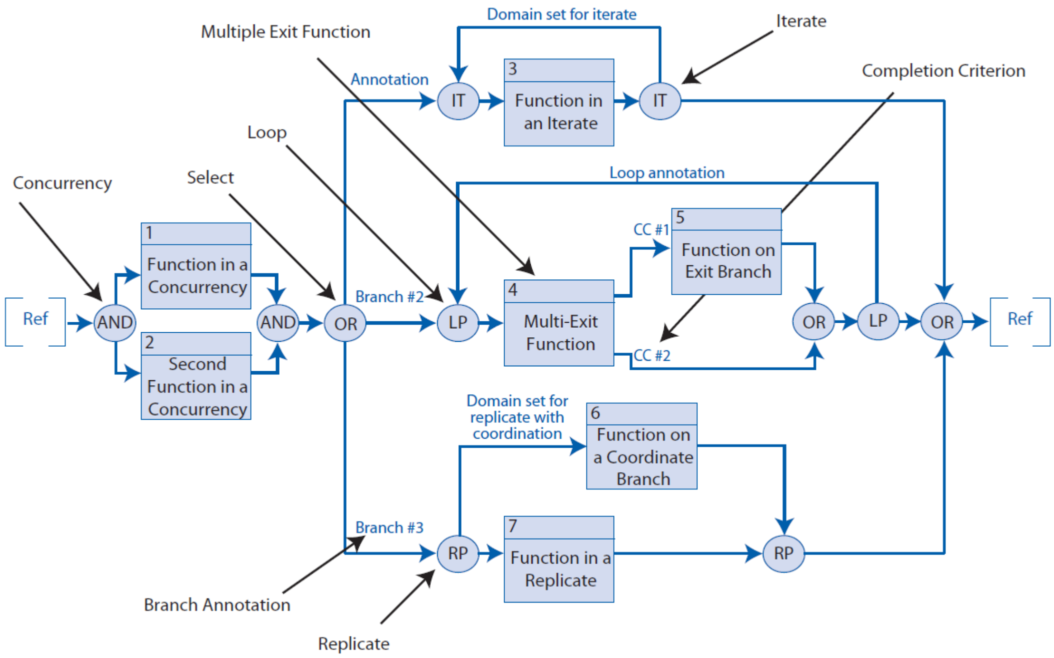


**Figure 3.4  FFBD example of System Behaviour**

Source: NASA (2007, p. 287)

EFFDB's expand on the FFBD language by adding a data flow overlay indicating data dependencies. An EFFBD specification of a system is complete enough so that it is executable as a discrete event model, capable of dynamic as well as static, validation. EFFBD's also provide the freedom to use either control constructs or data triggers to specify the execution conditions for system functions. Triggering inputs are typically indicated with double arrow heads (NASA, 2007).

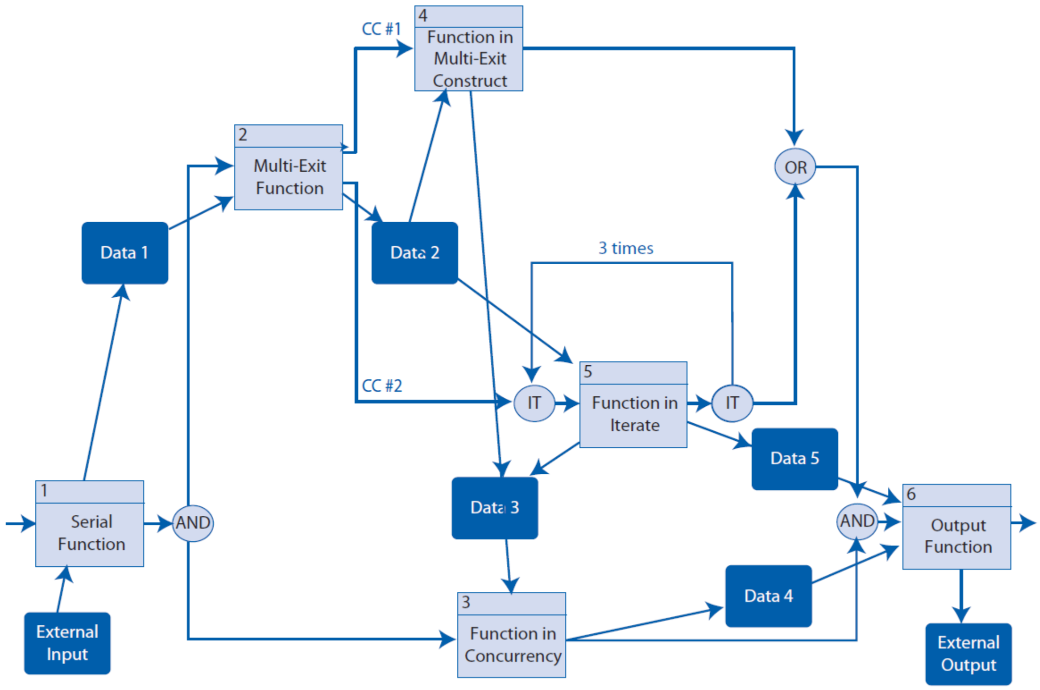


**Figure 3.5 EFFBD of System Behaviour**

Source: NASA (2007, p. 288)

## 3.4 DATA COLLECTION

The data collected in this study is qualitative in nature and takes the form of conceptual descriptions and descriptive models. This section describes the methods of data collection to be employed, covering the development and review of the pre-modelling concept of TFR signalling practices as well as the sample size and selection of the model development interviews. The section concludes with a description of interview planning, preparation and execution as well as a sample of interview questions to be included in the interviews.

### 3.4.1 Pre-modelling concept development and review

The pre-modelling conceptual framework of South African signalling practices is based on the researcher's own knowledge and experiences as a signalling engineer. Reference was made to written records and technical literature where possible. To make sure the framework was accurate, the resulting write-up was submitted to an experienced signalling engineer for review and comment.

### 3.4.2 Model development interview sample size and selection

Leedy & Ormrod (2015) defines the research sample as the source items from which researchers draw their data from. These sources may include people, objects, text materials and electronic records. The way in which this sample is identified, depends on the research question(s) asked. If inferences are to be drawn about the whole population, the ideal sample should be random and unbiased and presumed to be representative of the whole population.

Yet there are circumstances when a non-random sample is selected purposively and intentionally (Leedy & Ormrod, 2015). In such cases, the researcher may specifically select data sources that are most likely to help in the development of a theory (i.e. theoretical sampling). That same researcher may return to particular sources to help substantiate the theory (i.e. discriminant sampling). When selecting a sample, Leedy & Ormrod (2015) recommends the following:

- Samples should not only include the seemingly typical subject, but also non-typical examples.

- Intentionally look for cases that can potentially discredit emerging theories.

- If appropriate, select a sample from diverse contexts or situations.

In keeping with this, the research sample selected for this study consists of the following:

- A sample of three railway signalling engineers was selected. For confidentiality purposes these engineers were designated ENG1, ENG2 and ENG3.

- All three engineers were selected for their expertise as railway signalling engineers with extensive experience (30+ years) when it comes to TFR railway operations, signalling practices, projects and technologies.

- All three engineers were familiar to the researcher (also a railway signalling engineer). The railway signalling community within South Africa is quite small and most members are known to each other.

- Of the three engineers, only ENG3 is still directly employed by TFR.

- ENG1 was perceived by the researcher to be of a more conservative disposition, comfortable with the status quo and generally cautious when it comes to new methods and technologies.

- ENG2 was perceived by the researcher to be of a more open-minded and bold disposition and willing to explore new methods and technologies.

- ENG3 is not that well known to the researcher.

### 3.4.3 Model development interview planning, preparation and execution

In preparation for the model development interviews, letters were sent to candidates, requesting their participation, describing the nature of the interviews, interviewee responsibilities and ethical considerations. The contents of these letters were submitted for review to the university ethics committee during the research proposal phase of the project and were formally accepted. Interviews were also arranged to take place at a time and place deemed convenient by interviewees.

Before an interview was initiated, the interviewees were required to sign consent forms indicating they understood the nature of the interview, their rights and responsibilities as well as the associated ethical issues. The contents of this consent form was then submitted for review to the university ethics committee during the research proposal phase of the project and was formally accepted.

Interviews were in-depth and semi-structured and consisted of the development and review of the proposed ideal model by expert signalling engineers. Three separate interviews were arranged – one with each engineer. One or two simple modelling examples were discussed to familiarize the engineer with the modelling language. The background, motivations and recommendations upon which the model was to be based was explained and discussed with the engineers. Thereafter the engineers were required to develop and analyse the proposed model to confirm that the model could meet all the needs set out by the critical research question. When required, the engineer, aided by the interviewer, could modify the model to his satisfaction before signing-off. Any qualifying statements or comments were also recorded in the process.

Interviews were not recorded and transcribed verbatim. Interview notes, however, took the form of drawings, diagrams, descriptions and qualifying statements.

### 3.4.4 Sample of model development interview questions

The following sample interview questions were defined to bring a measure of consistency in the semi-structured interviews:

- Do you agree with the conclusions reached and recommendations made by the literature review?
- Is the proposed model based on current practices within TFR (current practice model)?
- Was the train driver function automation method recommended by the literature review implemented in the proposed ideal model?
- Should this method prove effective in the mitigation of SPADs?
- Can this model be considered as the 'most appropriate' within TFR railway operations?

## 3.5 DATA ANALYSIS

Data analysis took the form of the harmonization or consolidation of the interview models into a generic or representative model. This was possible due to the large degree of commonality between the models. When the models did diverge, the diverging features were highlighted and discussed as possible options or customizations that could be applied on top of the generic model.

## 3.6 STUDY VALIDTY AND RELIABILITY

Dudovskiy (2011) defines research validity as how well an instrument measures what it is intended to measure. If, for example, a scale reports the mass of a 4kg object as 3kg, the measurement is considered invalid and so is the instrument. Research validity can be divided into the categories of internal and external validity. Internal validity specifically speaks to the extent to which the research findings match reality while external validity speaks to the extent to which the research findings can be replicated in other environments.

Dudovskiy (2011), in turn, defines research reliability as the degree to which the method produces stable and consistent results. If, for example, a scale reports the mass of a 4kg object as 4kg at every measurement, the instrument is considered valid as well as reliable. If an incorrect value of 5kg was reported at every measurement, the instrument would still be considered reliable but not valid.

According to Leedy & Ormrod (2015), qualitative researchers may have difficulty applying these definitions as qualitative studies do not ‘measure’ things in the numerical way that quantitative studies do. Nevertheless, every study (qualitative of quantitative) should be concerned with the aspects of validity and reliability. Leedy & Ormrod (2015) has defined alternative concepts to describe validity and reliability when it comes to qualitative research. Rather than looking at the conventional validity of data, rather evaluate if the data is reasonably accurate with regards to the characteristics and dynamics of the entities or situation being studied. Similarly, instead of looking at the conventional reliability of qualitative data, rather evaluate the consistency in the patterns and dynamics these characteristics and dynamics reflect.

The case for the internal validity (or reasonable accuracy) of the research interview data used in this study consists of the following:

- As railway signalling engineers, interviewees are in a good position to evaluate the application and efficacy of train driver automation methods and the way they relate to train movement authorization and violation. As previously outlined, Railway signalling is the technical discipline that deals specifically with the challenge of train movements, movement authorization and railway safety.

- As senior railway signalling engineers with extensive experience in TFR operations and signalling systems, interviewees are in a good position to judge the proposed model for suitability in the TFR and greater South African railway context.

- The application of a graphical modelling language like EFFBD's instead of text based descriptions should reduce ambiguity of meaning and aid the interviewee in visualising and logically analysing the proposed model in an objective manner.

- Multiple (three) signalling engineers of differing dispositions and from different companies were interviewed. If the findings from the interviews are reasonably consistent, the instrument can be considered externally valid within the greater South African railway context.

- The technical review of the pre-modelling concept by one experienced signalling engineer was considered sufficient to verify it as reasonably accurate.

These measures should assure reasonable accuracy in the captured data.

Saunders et al. (2009) asserts that there may be four prominent threats to reliability when conducting interviews. Firstly, the subject or participant could make an error. The participant may give an incorrect answer due to tiredness or that his mind may be on some other task. Secondly, the subject or participant could have a bias. Loyalty to the company or fear of discovery might cause the participant to choose to deliver a good report instead of a true report. Thirdly, the observer or researcher may make an error. When conducting semi-structured interviews, the observer may be lead to investigate certain important angles in one interview that is not pursued in the others leading to inconsistencies. Lastly, the observer or researcher may have a bias. The observer may interpret a response to conform to his preferences instead of what was 'meant' by the respondent.

The case for the reliability (or reasonable consistency) of the research interview data used in this study consists of the following:

- A formalised and industry recognised model development process was followed (Robinson, 2004).

- Model development is an accepted research method and has been successfully applied in other studies (Shafique & Mahmood, 2010).

- Arranging interviews to be at times and locations that are convenient to interviewees, should minimise the effects of subject or participant error.

- Protecting the identities of interviewees and selecting them from multiple companies should minimise the effects of subject or participant bias.

- The preparation of a set of major interview questions that should be asked at every interview should minimise the effects of the participant observer (researcher) error.

- The application of a graphical modelling language like EFFBD's instead of text based descriptions should reduce ambiguity of meaning and aid the interviewee in visualising and logically analysing the proposed model in an objective manner. This measure should help to minimise the effects of observer bias.

- Multiple (three) signalling engineers of differing dispositions and from different companies were interviewed. If the findings from the interviews are reasonably consistent, the instrument can be considered reliable.

These measures should assure reasonable consistency in the captured data.

## 3.7 ETHICS CONSIDERATIONS

The following ethics considerations were identified as relevant to the study:

- Before any interviews could be conducted with signalling engineers about their TFR experience, TFR had to give permission. An application was submitted to TFR and permission was granted to proceed with the interviews.

- Due to the sensitive nature of research into SPADs and the causes of SPADs, the names of the interviewees were kept confidential.

Reference to interviewees was made by using code names only (i.e. ENG1). Any data captured during the interviews (audio, video, drawings and text) was also considered confidential. This information was stored on a secure data store with password protection. This data is to be stored for a period of 5 years after which it will be deleted or destroyed.

The ethics clearance reference number issued for this study is MIAEC 005/17.

## 3.8 RESEARCH PROJECT LIFECYCLE

Figure 3.6 is a summary representation of the resulting project lifecycle. The project was divided into distinct project proposal and implementation phases.

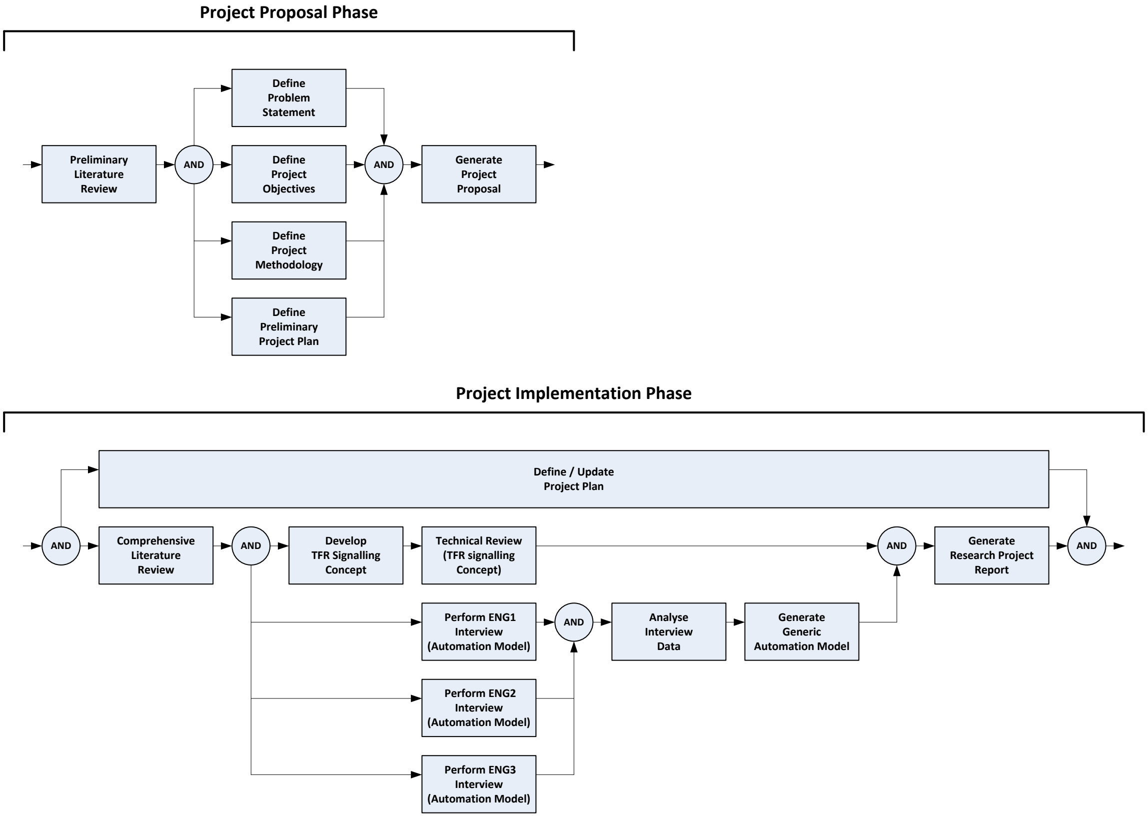


**Figure 3.6 Research Project Lifecycle**

# 4 RESULTS

This chapter will present the results collected in this study. This includes the conceptualization of signalling practices within TFR based on available technical documentation and reviews with experienced signalling engineers in addition to the data collected during modelling interviews with the experienced signalling engineers. The raw interview data is available in the appendix section.

## 4.1 CONCEPTUALIZATION OF SIGNALLING PRACTICES WITHIN TFR

The purpose of this section is to develop an understanding of how railway movements are effected within TFR, the roles and functions signalling system actors (the train driver and Train Control Officer (TCO) for example) and signalling system components (interlocking and field elements for example) play in those movements. This section presents an overview of railway signalling practices in TFR while highlighting the implications for SPAD incidents and causes.

Unfortunately, South Africa’s specific railway signalling principles, methods and technologies are not well documented in engineering manuals or guideline documents. This knowledge mostly resides within the minds of signalling engineers and has traditionally been transferred from one generation to the next by means of on-the-job training and mentoring processes. Although there may be a large degree of apparent international commonality in technologies and applications, the specific meanings of signals and signal aspects may differ, technologies may be applied in different ways and operational conventions and rules pertaining to train movements have been tailored to suit the local realities. This characteristic is best illustrated by the fact that all signalling systems and technologies procured for application in South Africa, have to go through a process commonly referred to as localization and type approval. During this process the supplier of the system or technology has to demonstrate compliance with local rules and practices including legacy system interfaces and may need to modify or customize his system for that purpose.  The localization and type approval before the implementation of signalling systems and technologies is considered to be standard practice in many countries around the world.

### 4.1.1 Functional Structure: Typical TFR Signalling and Operational Control System

A typical TFR Signalling and Control System can best be visualized in layers stacked on top of each other connecting the Train Control Officer (TCO), who represents railway operational objectives such as the train movement schedule, at the very top to the trains, and signalling field elements at the very bottom. Figure 4.1 has been adapted from Trinckauf's (2009) *Functional structure of the railway control system* to be more representative of TFR signalling and control. Refer to Figure 4.2 for an explanation of the symbols used.

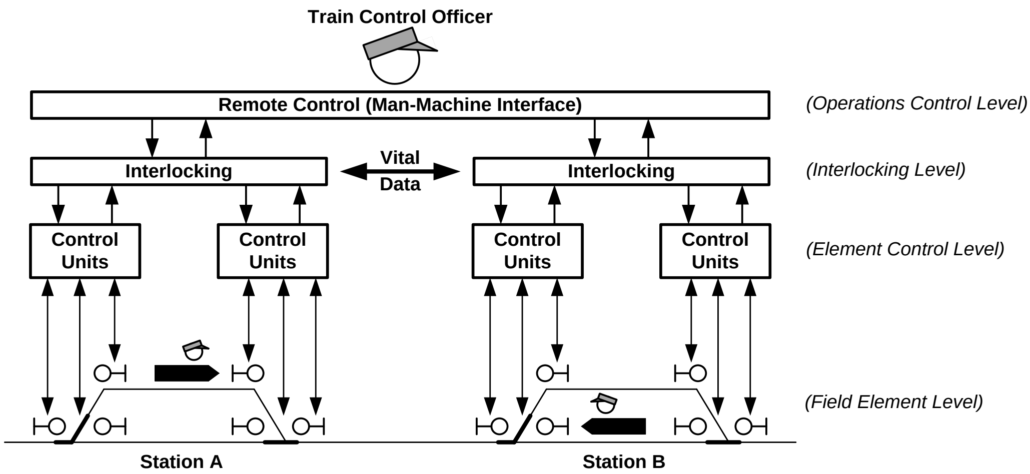


**Figure 4.1 Typical TFR Signalling & Operational Control System**

Source: Adapted from Trinckauf (2009, p. 21)

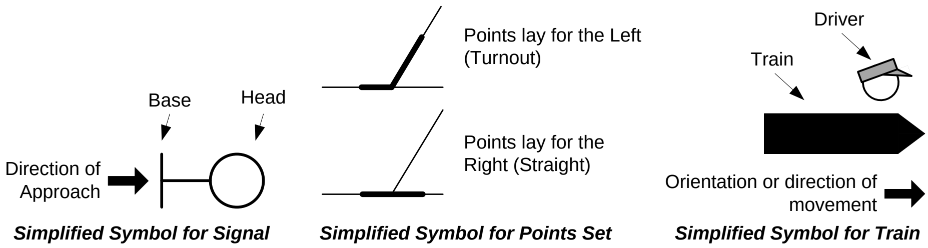


**Figure 4.2 Symbol Explanations of Field Elements**

### 4.1.2 Signalling for Railway Operation

At this point, it is appropriate to consider exactly how signals are used to facilitate safe railway movements on TFR lines. This section represents an application of the TFR train working rules (Spoornet, 2002) as well as the relevant functional requirements for signal interlocking systems implemented on TFR lines (Jooste, 2013).

**Principles of Train Separation**

The most common train separation methods include Signalled Fixed Block Operation and Cab Signal Operation of which the Fixed Block is the dominant method on TFR signalled lines (described in section 2.1.2).

On un-signalled TFR lines, constituting roughly 60% of all TFR lines, operational control is governed by a Track Warrant System (TWS). Movement authorities are managed within the in-house developed CS90 remote control and Visual Display Unit (VDU) system.

**Signals and Signal Aspects**

On TFR signalled lines the dominant practice is that of colour-light signalling with fixed block operation. This section will attempt to explain how signals are used to guide a train though a railway network, communicating compulsory movement authorities to the train driver who is then expected to follow them to the letter. As railway signalling rules, philosophies and applications are not universal and as practices within TFR specifically are the subject of this study, the latest TFR specific signalling rules and definitions (commonly referred to as multiple-aspect signalling) shall be applied in the explanations to follow.

Based on the role that signals play in Signalled Fixed Block Working and the basic requirement of providing a timely warning to train drivers, the functions of a signal can be listed to be the following:

a. Communication of movement authority into a block section including the nature of that authority (eg. permission to proceed and speed restrictions).

b. Inform the train driver as to the upcoming features of the track ahead (eg. upcoming turnouts, entry into yards and sidings).

As many different possible meanings have to be conveyed to the driver, the signal has been equipped with several different lamps of various colours and arranged in several different configurations. These lamps can then be activated in predetermined combinations to indicate specific meanings called signal aspects.

Figure 4.3 is a representation of a typical TFR signal that a driver would encounter when approaching a station (Jooste, 2013). On the left is the physical representation of the signal pole populated with a green lamp, red lamp, white lamp, two yellow lamps, a signal identification plate and a shunt lamp-set (two small white lamps arranged diagonally).

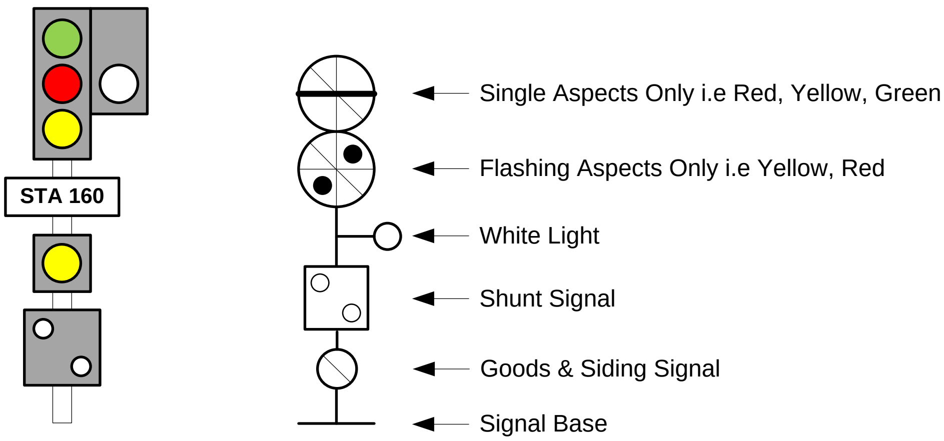


**Figure 4.3 Colour light signal (physical representation and symbology)**

Source: Adapted from Jooste (2013, pp. 117-121)

Source: Adapted from Transnet (1996, p. 36)

On the right side is a symbol of the same signal as it would be indicated on the engineering drawing of a signalling layout (Transnet, 1996). The symbol represents all of the different aspects that the given signal should be able to present.

Inside the circle at the top is indicated all the single aspects that the signal can present:

Vertical line: [Solid Green only] Proceed at line speed.

Diagonal line: [Solid Yellow only] Proceed but be prepared to stop at the next signal. The uppermost yellow lamp should be used for this aspect.

Horizontal line: [Solid Red only] Stop. The thicker line is used to indicate this is the default and most restrictive aspect the signal can present.

Inside the second circle from the top is indicated all of the flashing aspects the signal can present. The flashing nature of these aspects are indicated by the two solid black dots arranged diagonally inside the circle.

Diagonal line: [Flashing Yellow] Proceed at the correct speed for the train to turn out over one or more points sets (lower speed type) after this signal or the next. The uppermost yellow lamp should be used for this aspect.

Horizontal line: [Flashing Red] Emergency signal. Stop, then proceed in such a manner as to be able to stop within sighting distance.

The third item on the symbol is the white light that is used as an additional qualification on the other mainline proceed aspects. When combined with a solid green, flashing green or flashing yellow the white simply means that you should be prepared to stop at the 2nd signal ahead with the next signal located at less than the stopping distance from that stop signal.

The fourth item on the signal symbol is the shunt signal lamp-set. Shunt movements are special train movements used in train reconfiguration and staging and are usually confined to stations and stations yards. As these movements typically include trains being authorised onto occupied tracks, these movements are slow and are executed with the assistance of additional shunt personnel. This lamp-set is always combined with a solid red lamp to indicate that it is not a proceed authority but that the route is setup for a shunt movement and the driver should prepare to receive instructions from shunt personnel.

The last item on the symbol is a diagonal line inside a smaller circle. This is presented by a solid yellow on the second yellow lamp located on the signal. This lamp combined with the solid red is used to indicate to the driver he is about to enter a goods siding, typically un-signalled, and he should proceed on a by-sight basis with the understanding that the road is clear until the next control point.

It should then also be noted that in the case where none of the lamps are burning ("dark" signal) as may be the case in technical failure, the signal should be interpreted as a conventional stop signal, similar to the single solid red. If we add up all these different meanings or signal aspects, a signal with this physical configuration can be used to display up to thirteen different aspects.

So, how is this system used to communicate with the train driver? Figure 4.4 is a representation of a train approaching a station points set.

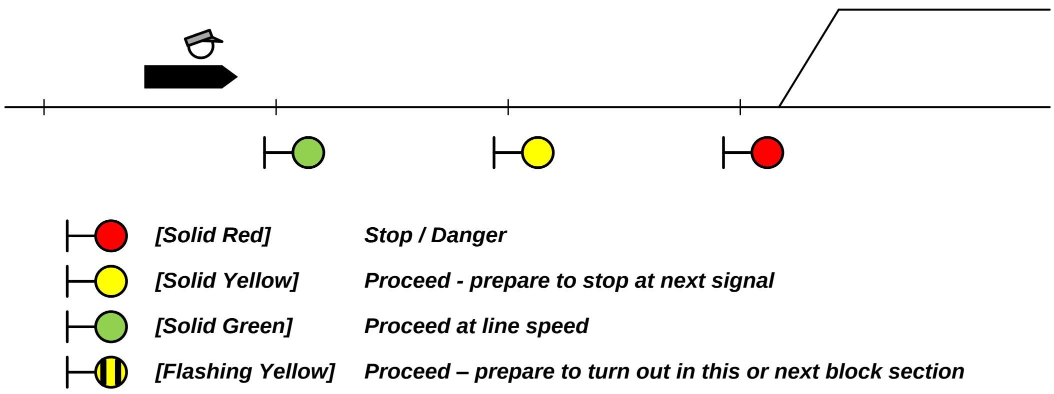


**Figure 4.4 Single aspects on the approach to a station**

The signal at the points is indicating Stop or "signal at danger". The signal directly in front of the driver is indicating he can safely proceed at line speed and from it he can deduce that the next signal he will encounter will also be at proceed, illustrating the fact that the driver can "see" roughly two signals ahead. As the driver proceeds to the next signal, he is notified that he can proceed with caution as he will be expected to stop at the following signal.

Figure 4.5 is another example of the application of flashing aspects. In both cases the flashing yellow is indicating that the driver may proceed and be prepared to turn out over a set of points in the next two sections.

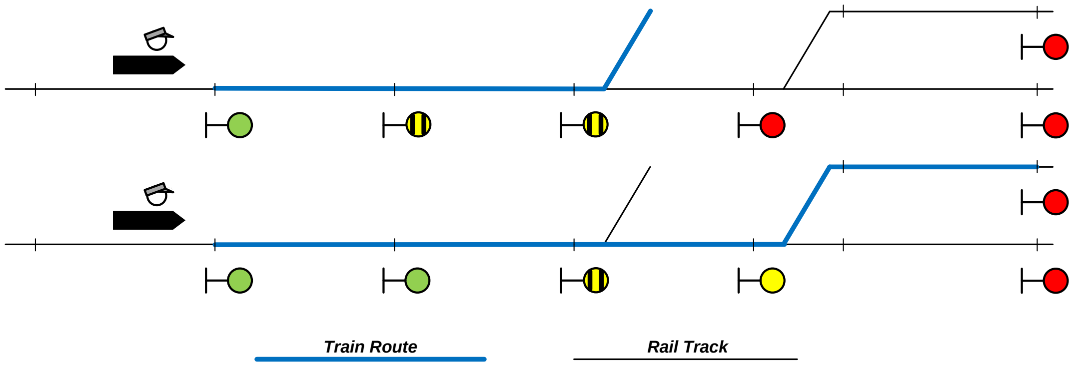


**Figure 4.5 Flashing aspects on approach to a turn-out**

The consequences of misreading or even completely missing a signal can vary from the benign to the severe. If a flashing yellow is misread as a solid yellow, the train may apply brakes and slow down too soon, simply resulting in an operational inefficiency. If the reverse happened (i.e. reading a solid yellow as a flashing yellow), the train will not slow down and prepare to stop at the stop signal ahead, possibly resulting in a train collision. If the white light that accompanied the green is missed, the train will come upon the signal warning them of the stop ahead with too little space to stop within. The worst case would obviously be to miss a stop signal or to come upon a stop signal unprepared which may result in a train collision while traveling at line speed.

**Interlocking Principles**

TFR interlocking systems typically implement the “Protected route and Overlap” method. TFR interlocked routes can also be manually cancelled by the TCO, but if the train has already entered the route or occupied the approach track to the entry signal, the signal is put back to Danger (stop/red aspect) but the route remains reserved and locked for a predetermined time before normalising. This prevents endangering the train and allows the driver to bring the train under control and to a safe stop without fear of a collision or derailment due to points being thrown under the train.

**Signalling a Layout (Crossing Station)**

The purpose of the crossing station is to increase bi-directional traffic density over a single line, albeit at the added cost of additional operational complexity. As traffic density demands increase, more and more crossing stations can be added, until traffic levels justify dedicated directional lines. Figure 4.6 illustrates a typical signalling layout for a crossing station.

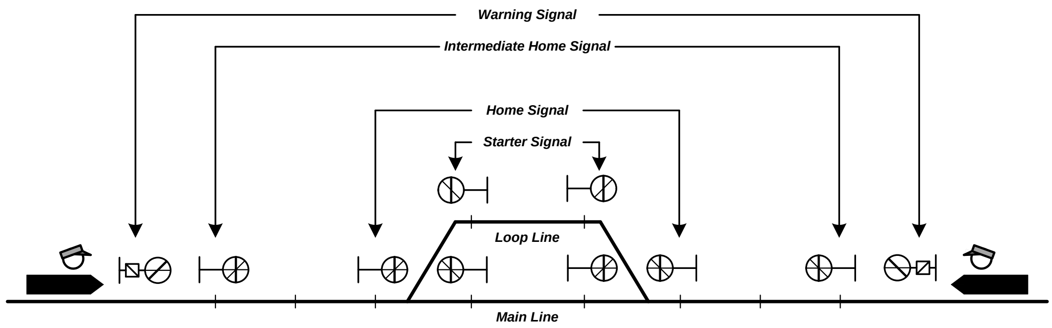


**Figure 4.6  Signalled Layout (Crossing Station)**

The purpose of the indicated signals in this layout are as follows:

Warning Signal: Warns the driver that he is approaching a stop signal. Note this signal does not have a Stop aspect. This signal is sometimes erroneously referred to as a distant signal.

Int. Home Signal: First stop signal when approaching the station and acts to protect the overlap of a route setup from the opposite side of the station.

Home Signal: Stop signal before station entry. This signal is to regulate access to the station.

Starter Signal: This signal has a dual purpose – it can either be used as a destination signal for a train entering the station (Danger Aspect) or as a departure signal for a train exiting the station (Proceed Aspect).

**Dispatching Principles**

Train movements over a railway network can be coordinated by means of either a de-centralised or centralised traffic control model.

In a Decentralised Operation the train movements are controlled by local interlocking stations. The TCOs of neighbouring interlocking stations communicate with each other by means of telecommunication, mostly by simple telephone connections (Pachl, 2009). This model is illustrated in Figure 4.7.

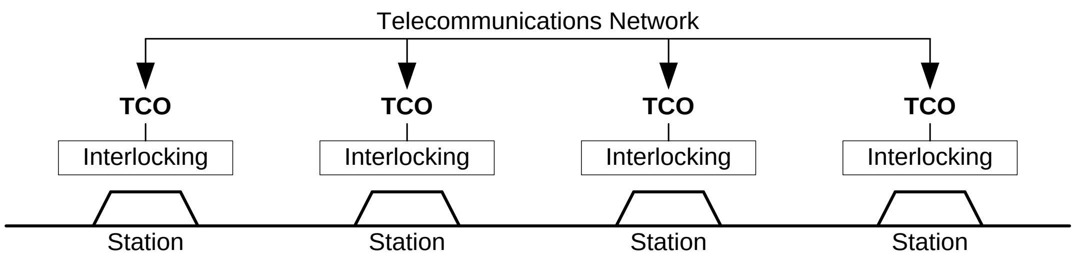


**Figure 4.7 Decentralised Operation**

Source: Adapted from Pachl (2009, p. 59)

In Centralised Traffic Control (CTC), all points and signals inside the controlled area are directly controlled by the CTC TCO. All train movements are governed by signal indications. The local interlockings are remote-controlled without local staff (Pachl, 2009). CTC operation is the predominant model on TFR lines. This model is illustrated in Figure 4.8.

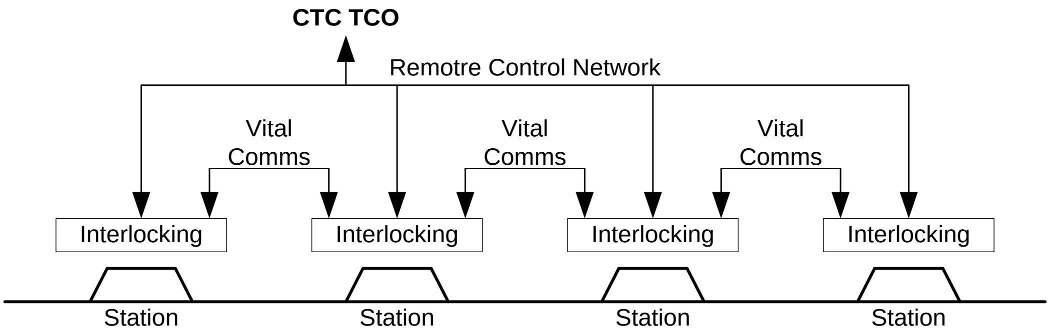


**Figure 4.8 Centralised Traffic Control (CTC)**

Source: Adapted from Pachl (2009, p. 60)

## 4.2 ENG1 INTERVIEW DATA

ENG1 listed two distinct modes of train authorization within TFR that may be relevant to this study. Refer to appendix 9.1 for the detailed summary of the interview. They comprise those of fully fledged signalled operations and those of Track Warrant operations. Yet, in his estimation, the fact that Track Warrant operations are considered such a low safety risk as to not justify being upgraded to fully signalled operations does not recommend them for driver automation upgrades to mitigate SPADs. The only mode authorization to be modelled, was that of fully fledged signalled operations.

ENG1 generally agreed with the assessment and recommendations from the literature review. In his estimation the model should at least be based on an Automatic Train Protection (ATP) system that intervenes by applying the brakes if the train driver is found to exceed the speed limit or required braking curve to successfully stop in front of a stop signal. Lastly, the system should be applicable to train movements both within and between stations, the driver should not be able to override the safety system and it should be able to be installed on most locomotives.

ENG1 also identified the enforcement of optimal speed and driving profiles a significant advantage to counter what he called “malicious driver behaviour” which he considered to be a major problem on South African railways. Such behaviour would typically include a driver driving the train at a significantly lower than optimal speed so as to extend his shift and become eligible for overtime. The system should therefore guide the driver towards optimal speed profiles typically by means of an in-cab display presenting a speed target window for the train to stay within.

#### 4.2.1.1 Fully Signalled Operation (FSO)

Figure 4.9 is a representation of the typical train movement to be used as the basis for the modelling exercise.

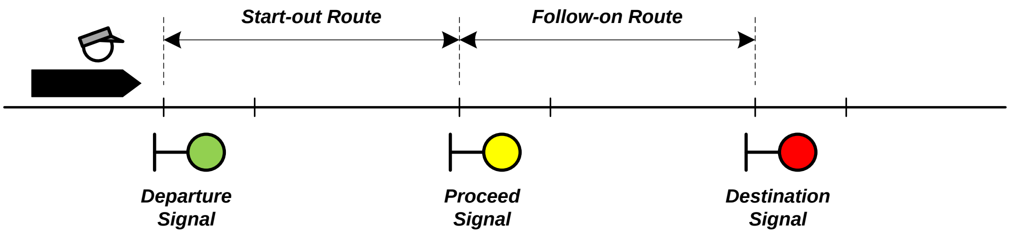


**Figure 4.9 Train Movement in Fully Signalled Operation**

Figure 4.10 is a representation of the resulting systems structure for the Current Practice (CP) model.

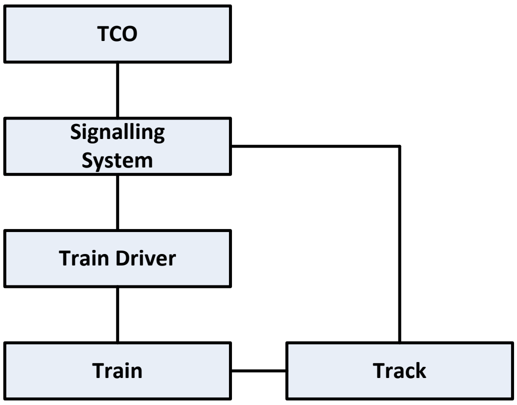


**Figure 4.10 System Structure – FSO, CP Model, ENG1**

Interface listing:

- TCO – Signalling System: Computer based control terminal
- Signalling System – Track: Train detection device (axle counter / track circuit)
- Signalling System – Train Driver: Signal lamp
- Train Driver – Train: Driver instrument panel
- Train – Track: Wheel on track

For practical and presentation purposes, the behaviour model was segmented into three distinct phases:

- Phase1 – Movement Setup (Figure 4.11)
- Phase2 – Route Traversal (Figure 4.12)
- Phase3 – End of Authority (Figure 4.13)

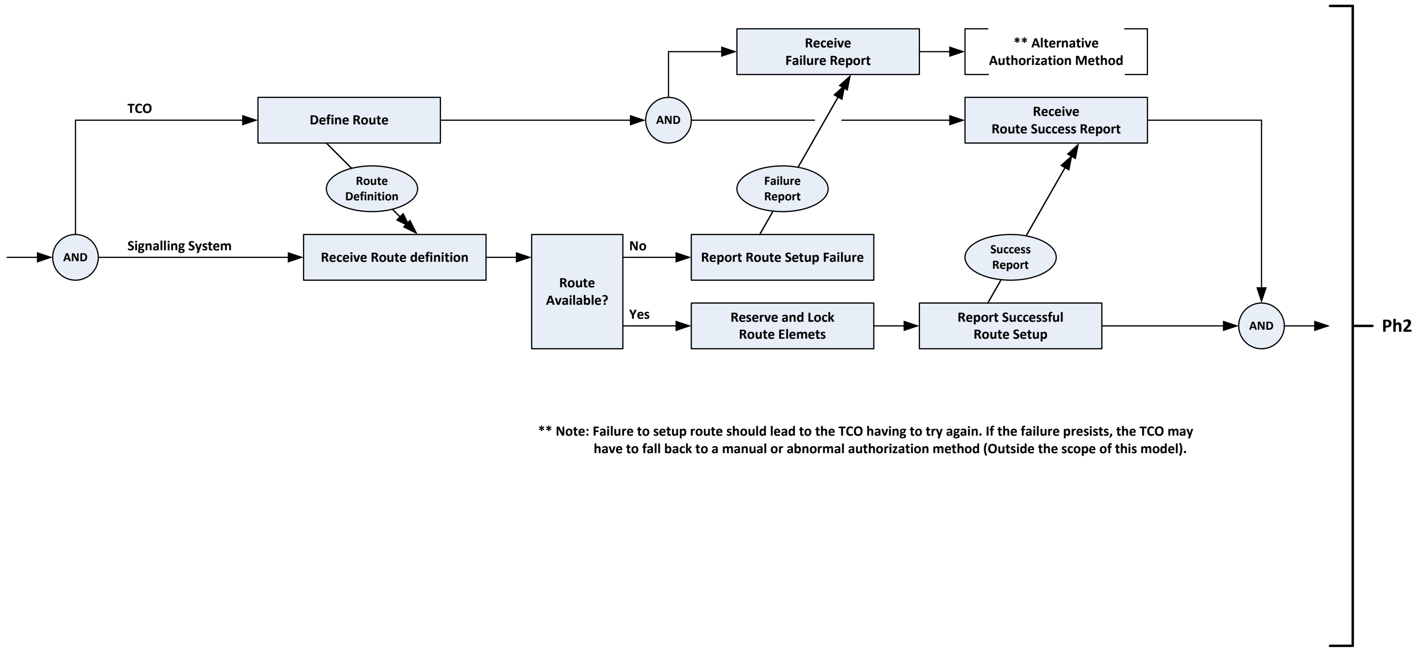


**Figure 4.11 System Behaviour Phase1 (Movement Setup) – FSO, CP Model, ENG1**

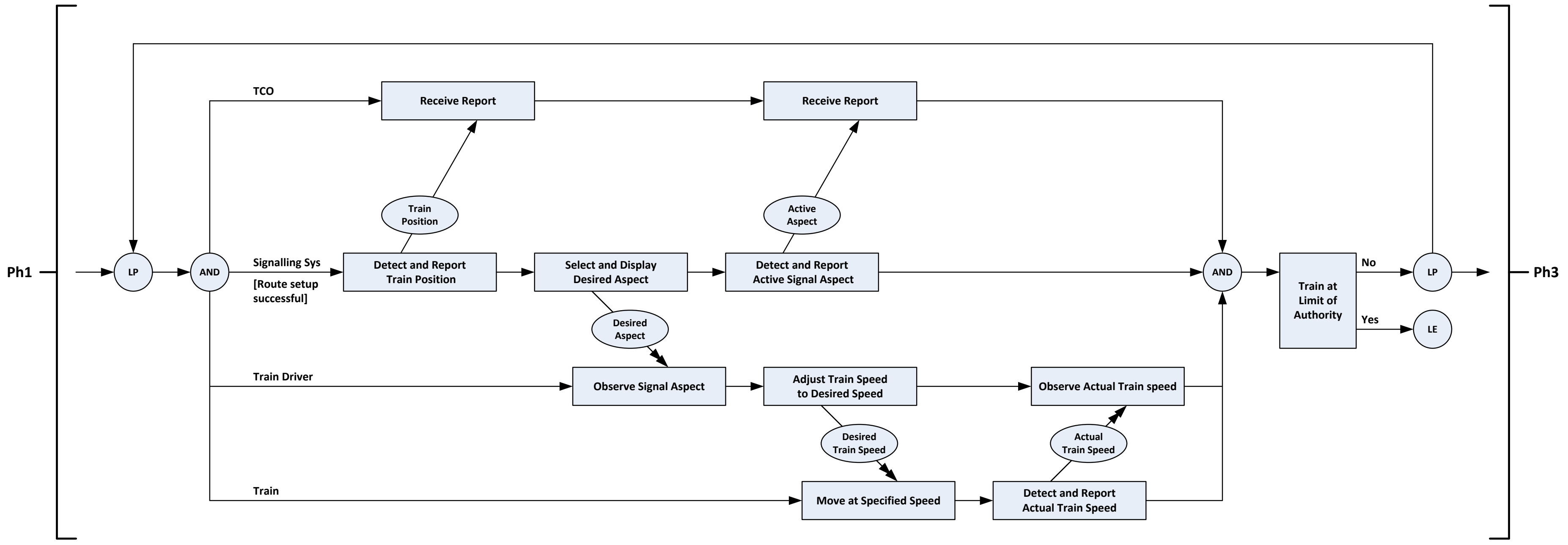


**Figure 4.12 System Behaviour Phase2 (Route Traversal) – FSO, CP Model, ENG1**

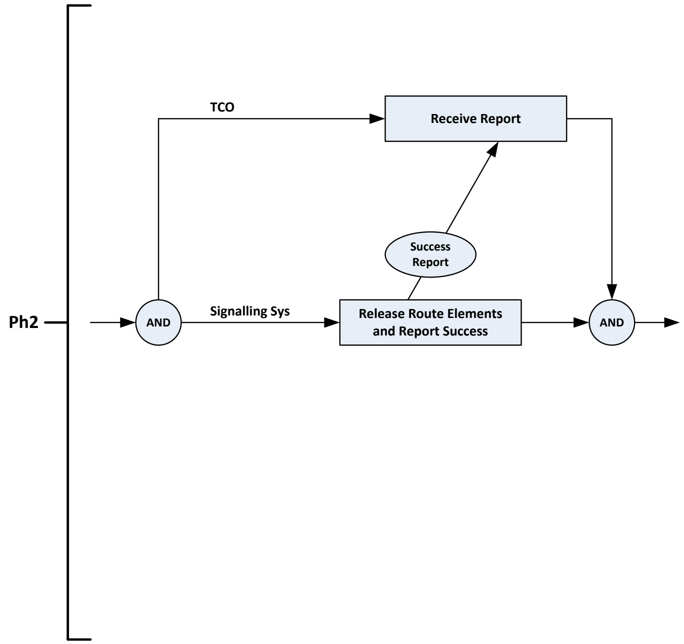


**Figure 4.13  System Behaviour Phase3 (End of Authority) – FSO, CP Model, ENG1**

The modifications introduced during the development of the Proposed Automation (PA) model is indicated in **BLUE**. This model also specifically shows what would happen if a driver fails to keep within the required speed limits. The structure and behaviour of Phase1 (Movement Setup) and Phase3 (End of Authority) remained unchanged from the CP model.

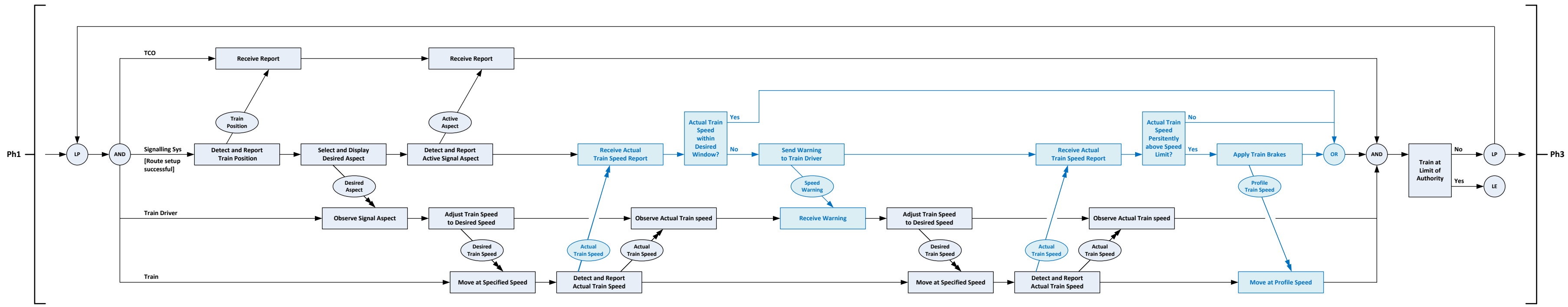


**Figure 4.14 System Behaviour Phase2 (Route Traversal) – FSO, PA Model, ENG1**

When presented with the following interview questions regarding the proposed automation model, ENG1 answered all of them in the affirmative:

a. Was the train driver function automation method recommended by the literature review implemented in the proposed ideal model?

b. Should this method prove effective in the mitigation of SPADs?

c. Can this model be considered as the ‘most appropriate’ within TFR railway operations?

## 4.3 ENG2 INTERVIEW DATA

ENG2 also listed the two distinct modes of train authorization within TFR relevant to this study to be those of fully fledged signalled operations and those of Track Warrant operations but required both to be considered for driver automation upgrades. Refer to appendix 9.2 for the detailed summary of the interview.

ENG2 generally agreed with the assessment and recommendations from the literature review. In his estimation the model should be based on an Automatic Train Protection (ATP) system that intervenes by applying the brakes if the train driver is found to exceed the speed limit or required braking curve to successfully stop in front of a stop signal. Lastly, the system should not impact the train working rules, prioritize safety above productivity and in the implementation thereof there should be consequences for the driver if found to drive poorly.

#### 4.3.1.1 Fully Signalled Operation

The typical train movement used in the modelling exercise was the same as that for ENG1 (refer to Figure 4.9).

Figure 4.15 is a representation of the resulting systems structure for the Current Practice (CP) model.

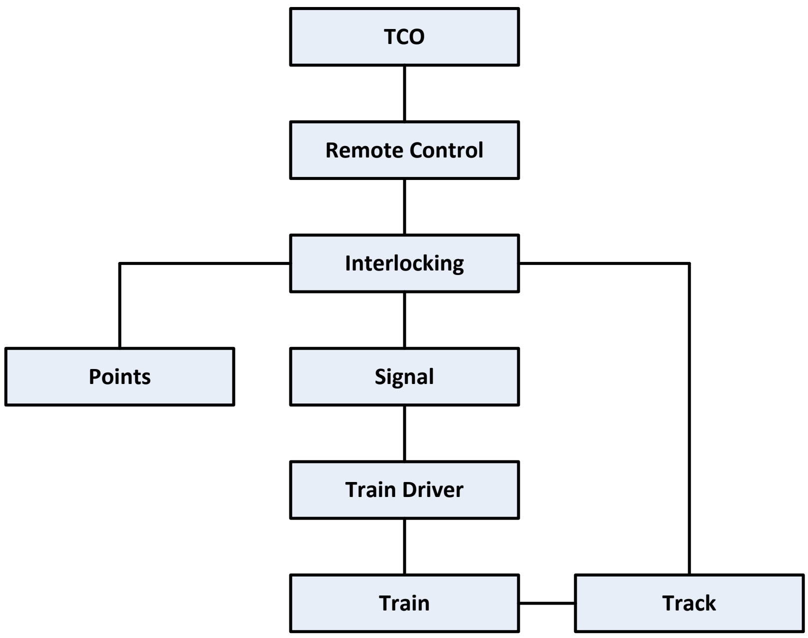


**Figure 4.15 System Structure – FSO, CP Model, ENG2**

Interface listing:

- TCO – Remote Control: Computer based control terminal
- Remote Control – Interlocking: Communications network
- Interlocking – Points: Points blade detection device
- Interlocking – Signal: Lamp drive circuit
- Interlocking – Track: Train detection device (axle counter / track circuit)
- Signal – Train Driver: Signal lamp (Optical)

- Train Driver – Train: Driver instrument panel
- Train – Track: Wheel on track

For practical and presentation purposes, the behaviour model was segmented into three distinct phases:

- Phase1 – Movement Setup (Figure 4.16)
- Phase2 – Route Traversal (Figure 4.17)
- Phase3 – End of Authority (Figure 4.18)

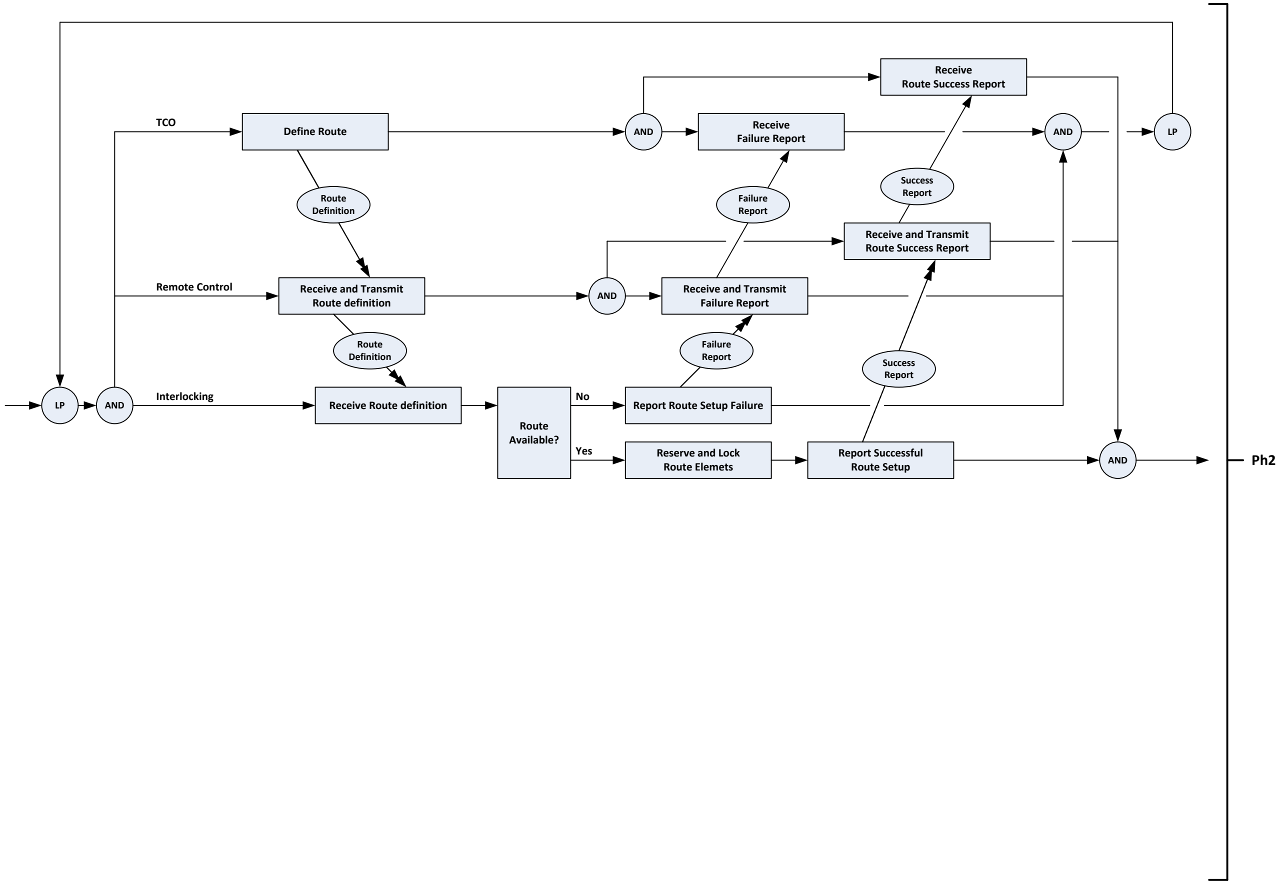


**Figure 4.16 System Behaviour Phase1 (Movement Setup) – FSO, CP Model, ENG2**

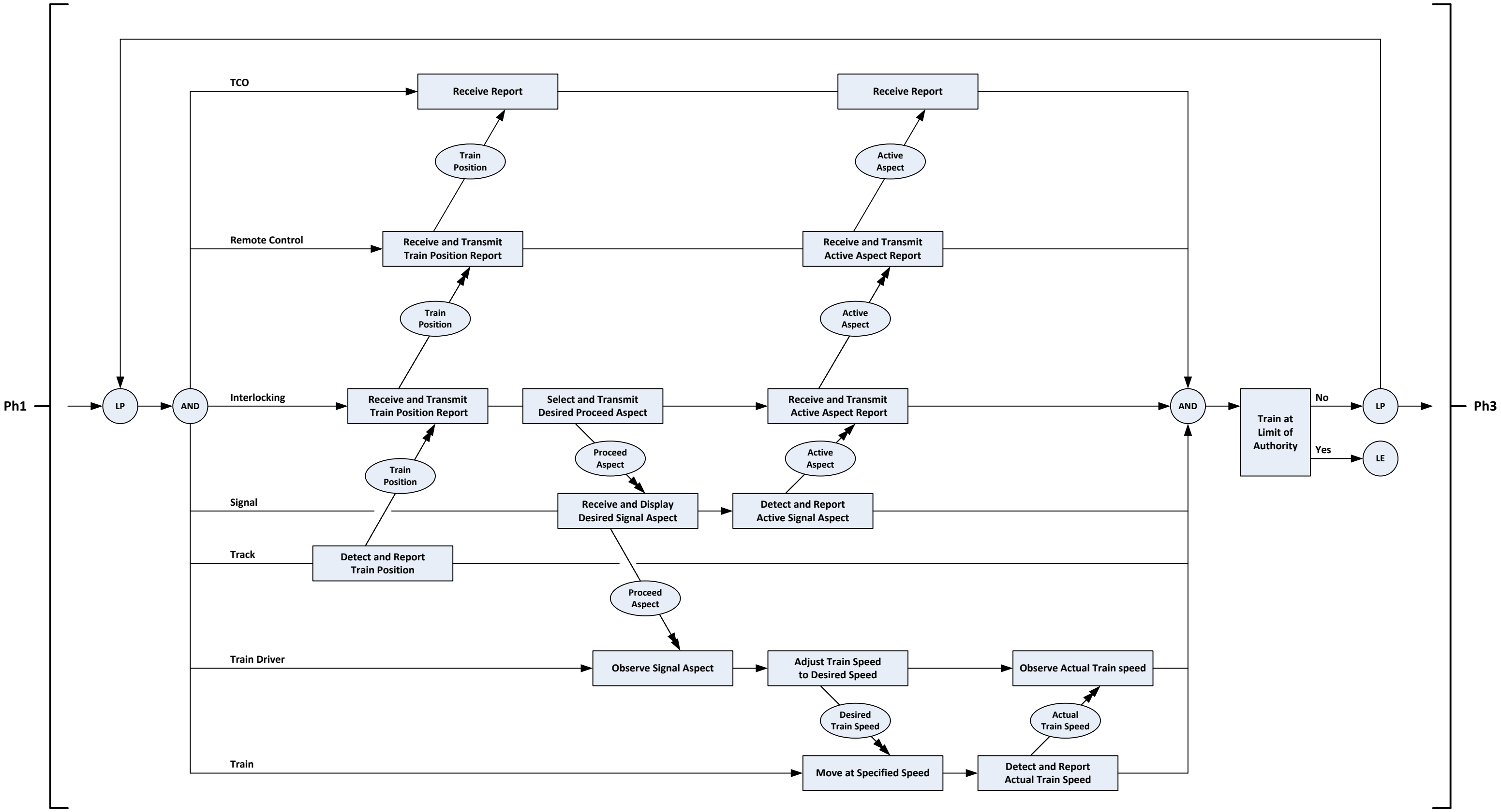


**Figure 4.17 System Behaviour Phase2 (Route Traversal) – FSO, CP Model, ENG2**

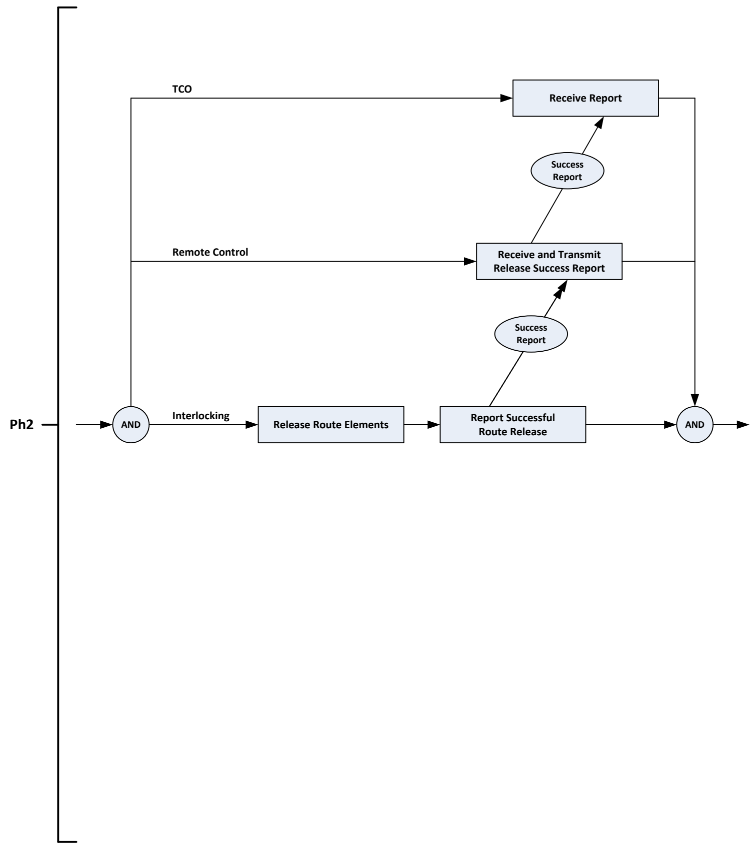


**Figure 4.18 System Behaviour Phase3 (End of Authority) – FSO, CP Model, ENG2**

The modifications introduced during the development of the Proposed Automation (PA) model are indicated in **BLUE**. This model also intentionally shows specifically what would happen if a driver fails to keep to the required speed limits. The behaviour of Phase1 (Movement Setup) and Phase3 (End of Authority) remained unchanged from that of the CP model.

Figure 4.19 and Figure 4.20 are updated versions of the system structure and system behaviour Phase2 (Route Traversal) that represents the PA model.

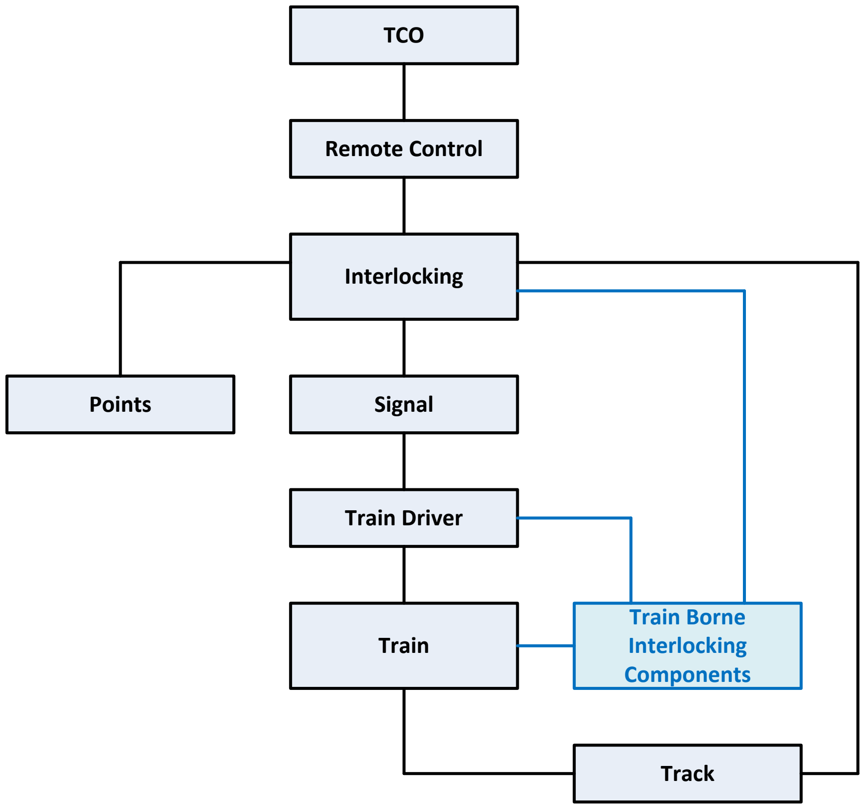


**Figure 4.19 System Structure – FSO, PA Model, ENG2**

Interface listing:

- TCO – Remote Control: Computer based control terminal
- Remote Control – Interlocking: Communications network
- Interlocking – Points: Points blade detection device
- Interlocking – Signal: Lamp drive circuit
- Interlocking – Track: Train detection device (axle counter / track circuit)
- Interlocking – Train Borne Interlocking Components: Safety critical communications network
- Signal – Train Driver: Signal lamp (Optical)
- Train Driver – Train: Driver instrument panel
- Train Driver – Train Borne Interlocking Components: Visual display terminal
- Train – Train Borne Interlocking Components: Instrumentation suite (including speedometer and odometer)
- Train – Track: Wheel on track

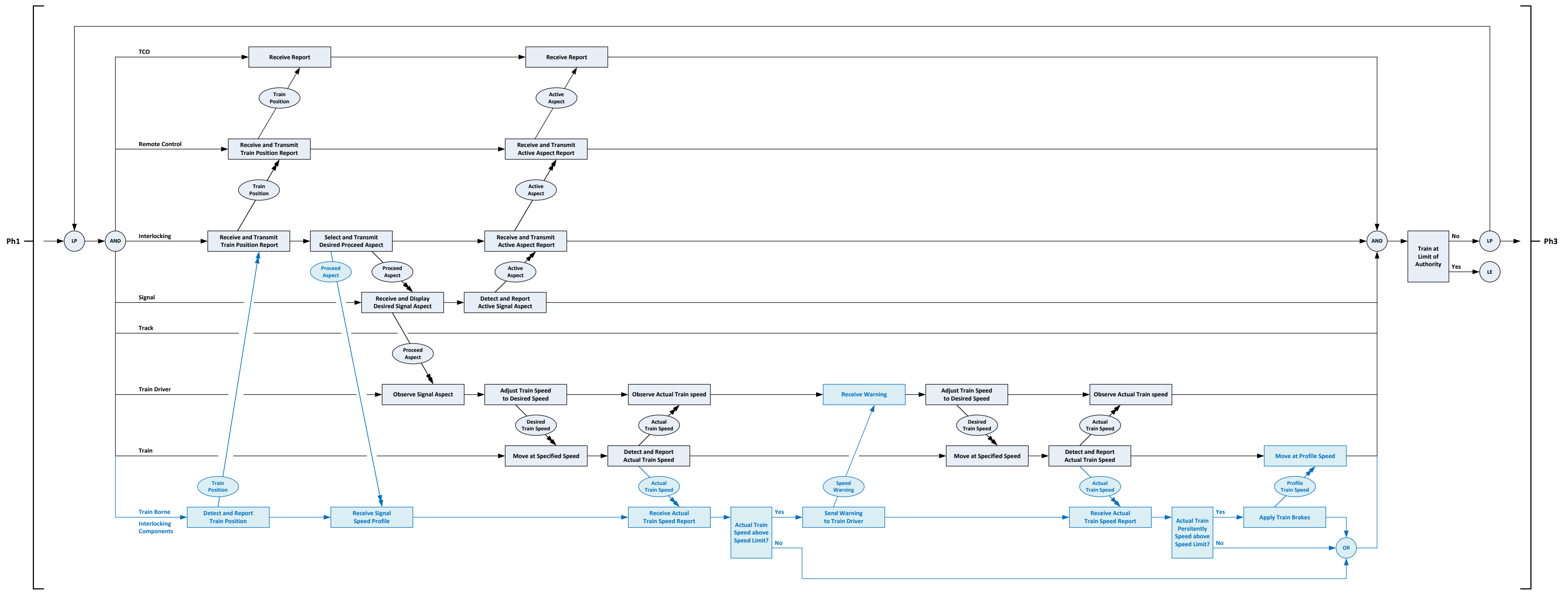

**Figure 4.20 System Behaviour Phase2 (Route Traversal) – FSO, PA Model, ENG2**

#### 4.3.1.2 Track Warrant Operation (TWO)

Figure 4.21 is a representation of the typical train movement to be used as the basis for the modelling exercise.

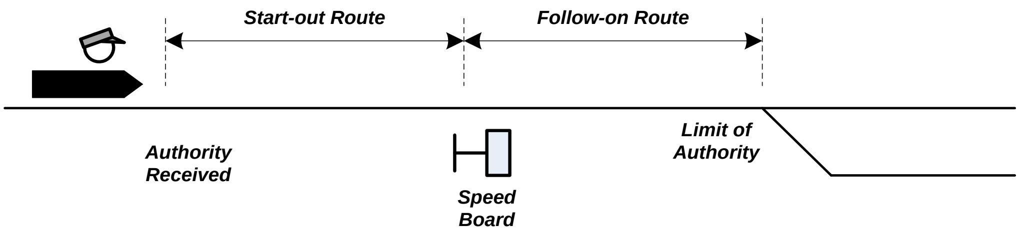


**Figure 4.21 Train Movement in Track Warrant Operation**

Figure 4.22 is a representation of the resulting systems structure for the Current Practice (CP) model. The “signalling element” component was added for completeness after the interview was completed as it was present in the behaviour diagram but missing in the structure diagram.

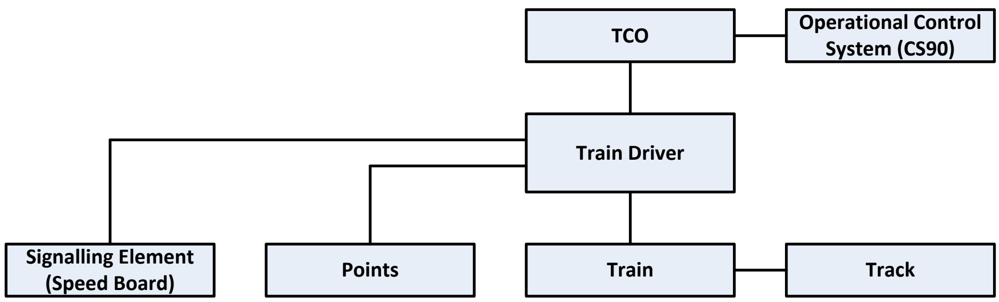


**Figure 4.22 System Structure – TWO, CP Model, ENG2**

Interface listing:

- TCO – Operational Control System: Computer based control terminal
- TCO – Train Driver: Radio / Cellular phone
- Train Driver – Signalling Element: Notice board (Optical)

- Train Driver – Points: Visually observed (Optical)
- Train Driver – Train: Driver instrument panel
- Train – Track: Wheel on track

For practical and presentation purposes, the behaviour model was segmented into three distinct phases:

- Phase1 – Movement Setup (Figure 4.23)
- Phase2 – Route Traversal (Figure 4.24)
- Phase3 – End of Authority (Figure 4.25)

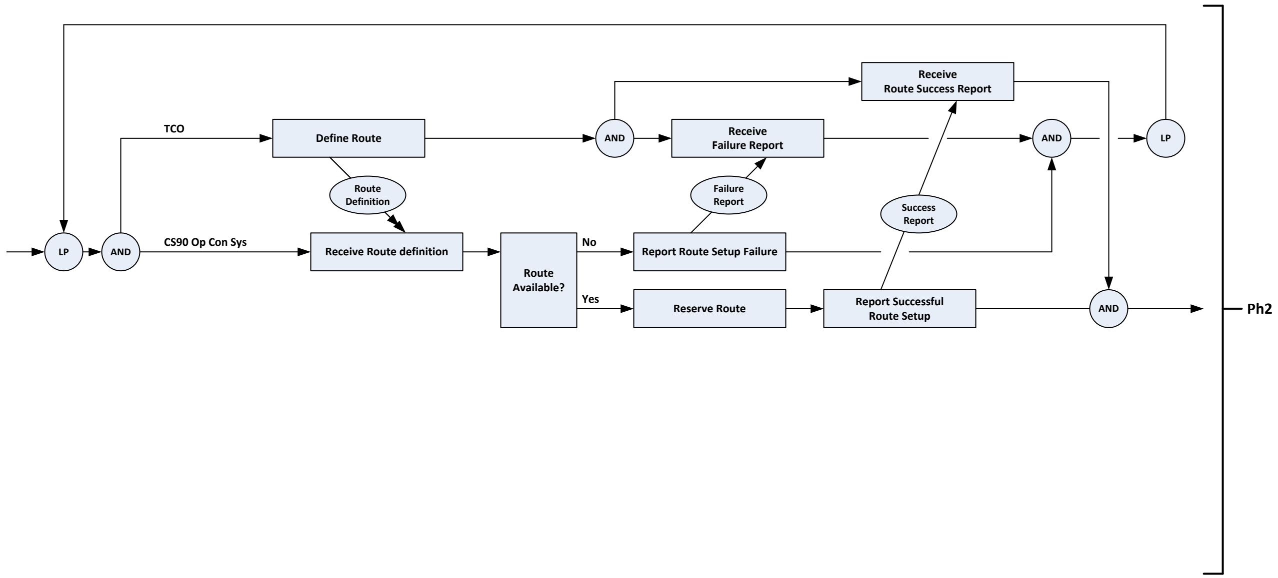


**Figure 4.23 System Behaviour Phase1 (Movement Setup) – TWO, CP Model, ENG2**

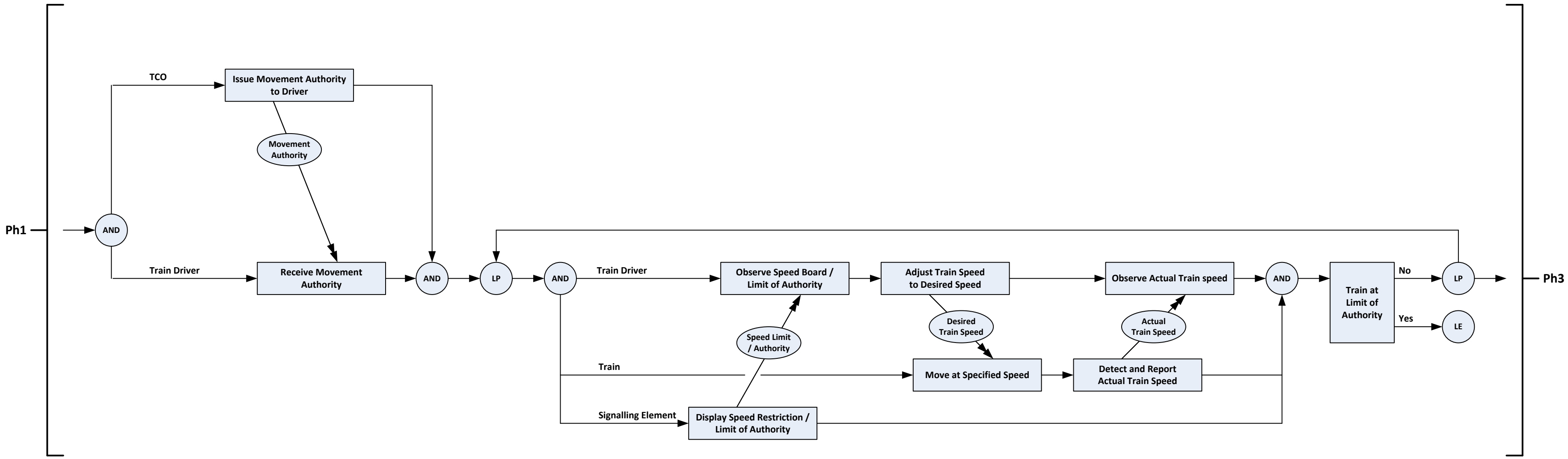


**Figure 4.24 System Behaviour Phase2 (Route Traversal) – TWO, CP Model, ENG2**

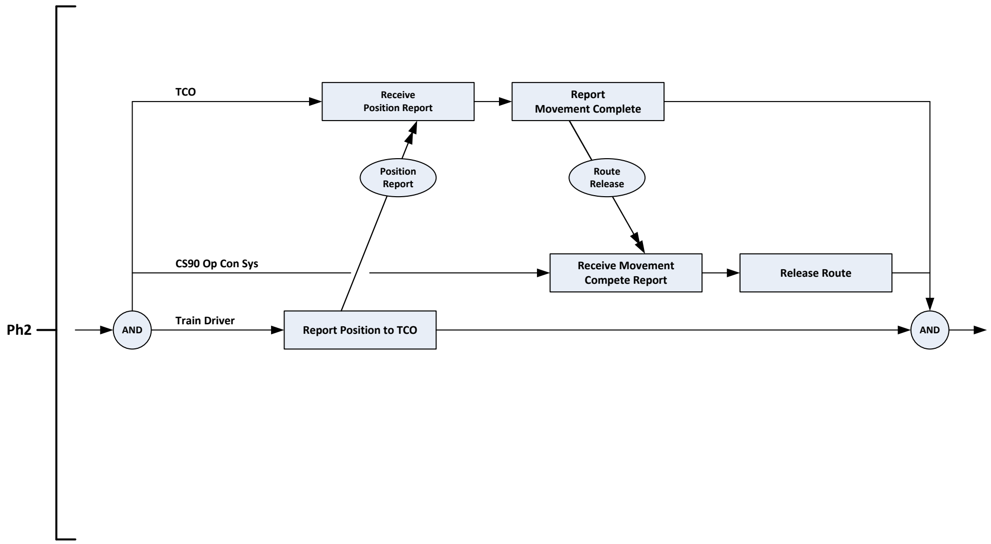


**Figure 4.25  System Behaviour Phase3 (End of Authority) – TWO, CP Model, ENG2**

The modifications introduced during the development of the Proposed Automation (PA) model is indicated in **BLUE**. This model also specifically shows what would happen if a driver fails to keep to the required speed limits. The behaviour of Phase3 (End of Authority) remained unchanged from that of the CP model.

Figure 4.26, Figure 4.27 and Figure 4.28 are updated versions of the system structure and system behaviour Phase1 (Movement Setup) and Phase2 (Route Traversal) that represents the PA model. The “signalling element” component was added for completeness after the interview was completed as it was present in the behaviour diagram but missing in the structure diagram.

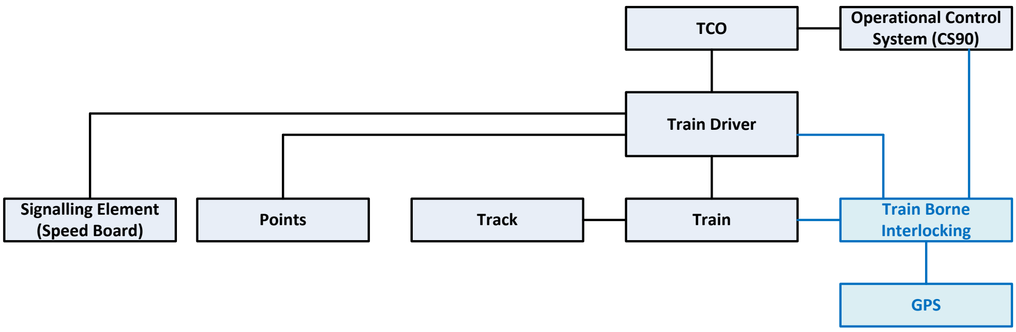


**Figure 4.26  System Structure –TWO, PA Model, ENG2**

Interface listing:

- TCO – Operational Control System: Computer based control terminal
- TCO – Train Driver: Radio / Cellular phone
- Operational Control System – Train Borne Interlocking: High-integrity communications network
- Train Driver – Signalling Element: Notice board (Optical)
- Train Driver – Points: Visually observed (Optical)
- Train Driver – Train: Driver instrument panel

- Train Driver – Train Borne Interlocking: Visual display terminal
- Train – Track: Wheel on track
- Train – Train Borne Interlocking: Instrumentation suite (including speedometer and odometer)
- Train Borne Interlocking – GPS: Satellite communication

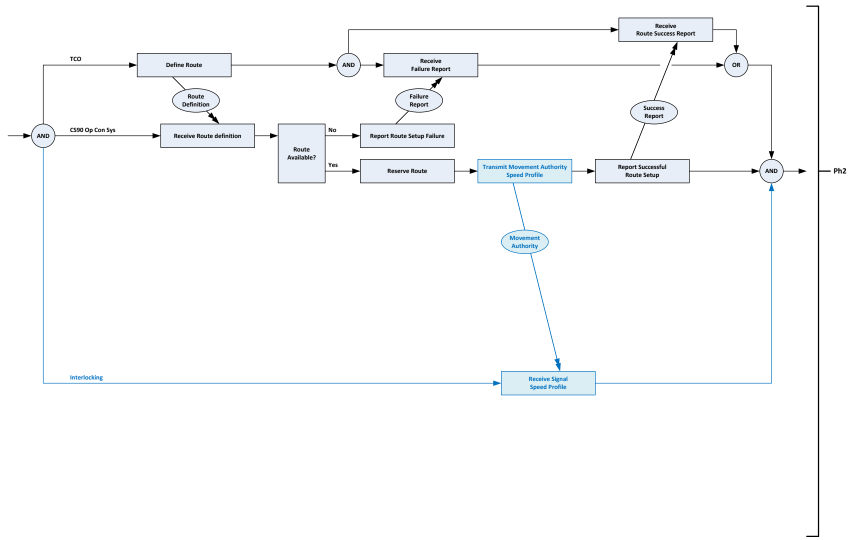


**Figure 4.27 System Behaviour Phase1 (Movement Setup) – TWO, PA Model, ENG2**

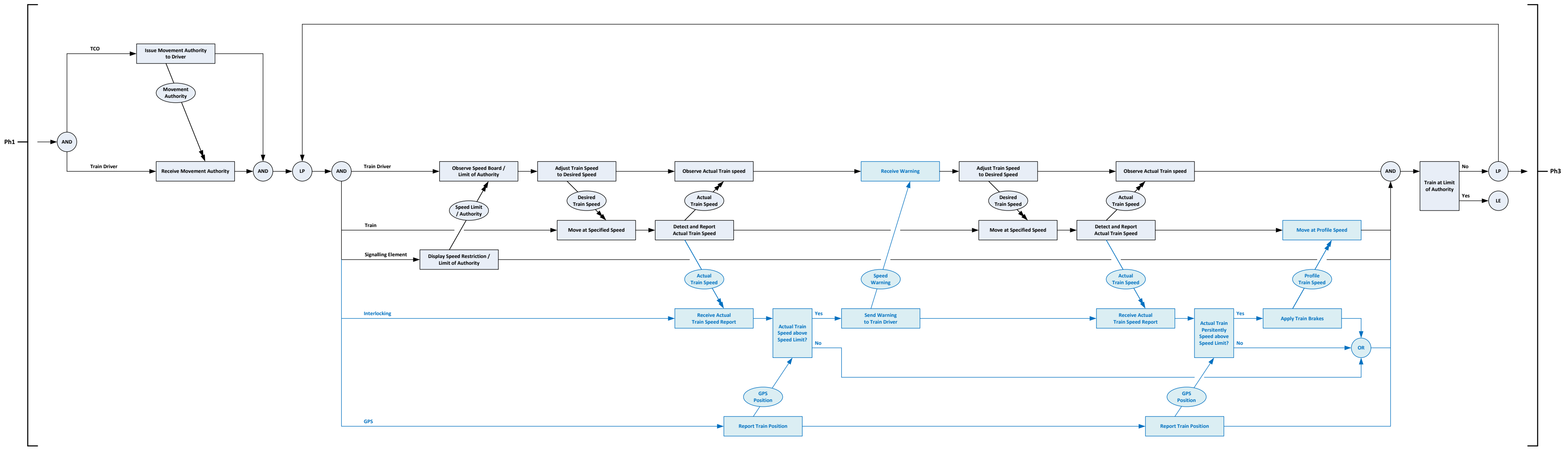


**Figure 4.28 System Behaviour Phase2 (Route Traversal) – TWO, PA Model, ENG2**

When presented with the following interview questions regarding the proposed automation models, ENG2 answered all of them in the affirmative:

a. Was the train driver function automation method recommended by the literature review implemented in the proposed ideal model?

b. Should this method prove effective in the mitigation of SPADs?

c. Can this model be considered as the ‘most appropriate’ within TFR railway operations?

### 4.4 ENG3 INTERVIEW DATA

Due to the large degree of commonality between the Current Practice models and the Proposed Automation models produced by ENG1 and ENG2, the interview format for ENG3 was rather directed towards the confirmation or rejection of those models Refer to appendix 9.3 for the detailed summary of the interview. ENG3 was therefore presented with consolidated versions of the recommendations and models from ENG1 and ENG2 and asked for his evaluation.

ENG3 generally agreed with the assessment and recommendations from the literature review as well as the recommendations and the consolidated models produced from those generated by ENG1 and ENG2 (Current Practice as well as Proposed Automation models). When also presented with the same three interview questions regarding the consolidated proposed automation model, ENG3 answered all of them in the affirmative.

The consolidated and now accepted versions of the Current Practice and Proposed Automation models will be presented and discussed in the next chapter (chapter 5).

# 5 ANALYSIS

This chapter will present an analysis of the model data collected in this study and propose a consolidated or generic train driver function automation model than can be considered most appropriate for the TFR environment. This analysis includes the description and discussion of the commonalities and differences for both the Current Practice and Proposed Automation models as well as motivation for the final selection of the most appropriate model.

It should be noted that the actual models generated in the interview process did not always strictly adhere to the proper notation conventions associated with the EFFBD modelling language. Examples of such deviations include:

- A concurrency structure that start with a single “AND” operation and terminate in two separate “AND” operations due to logical branches introduced in between (See Figure 4.16). The “Kill” command was also used to indicate the termination of other branches when particular branch completed its run first.

- A concurrency structure (AND) that is initiated but is not terminated (see Figure 4.11) or an OR operation erroneously used to terminate an AND structure (see Figure 4.27).

- Sometimes functions or data items were not given unique names. A typical example can be seen in Figure 4.12 where a generic function “Receive Report” is called in multiple instances even though different kinds of reports are received in those instances.

- Data item flows or exchanges between functions within the same branch were not shown as they would introduce a lot of clutter and complication to behaviour diagrams. On the other hand, the indication of data item flows between branches (effectively, data flows between system components) were considered essential.

- Behaviour branches with no activity were not included on behaviour diagrams. These branches were only shown when they became active. In Figure 4.11 the behaviour branches for the train driver and the train are not shown. As soon as those components become active, their branches are also shown (Figure 4.12). This was done limit clutter.

As these models were intended to be primarily descriptive, these deviations were not considered problematic as long as the models were readable, understandable, logical and unambiguous. Per implication, these models may require a measure of reformulation if they are to be ported into software tools for simulation purposes.

## 5.1 CURRENT PRACTICE MODEL

There is a large degree of commonality between the Current Practice models generated by ENG1 an ENG2. This is not unexpected for the following reasons:

- Both engineers are describing the actual practices in an industry in which both have practiced for decades.

- Both models were drawn by the researcher while being guided and criticized by the interviewees. It can be expected the models would therefore reflect the way that the researcher visualized the structure and behaviour of the modelled system, whilst also being considered accurate by the responsible interviewee.

The major differences between the models generated by ENG1 and ENG2 are:

- ENG1 did not generate a model for Track Warrant operations.

- ENG1 described behaviour of the signalling system as a whole where ENG2 preferred to include the structure and behaviour of signalling system components including the interlocking, remote control and train-borne system components.

These differences do not represent a contradiction or even a serious deviation for the following reason. If the level of detail in the ENG2 Current Practice model is reduced to the signalling system level, the differences between the model by ENG1 and the models by ENG2 (both FSO and TWO models) become that of technological implementation only and not of methodology. This view, together with the resulting model presented below (generic CP model), was confirmed in the ENG3 interview:

- Structure (Figure 5.1)
- Phase1 – Movement Setup (Figure 5.2)
- Phase2 – Route Traversal (Figure 5.3
- Phase3 – End of Authority (Figure 5.4)

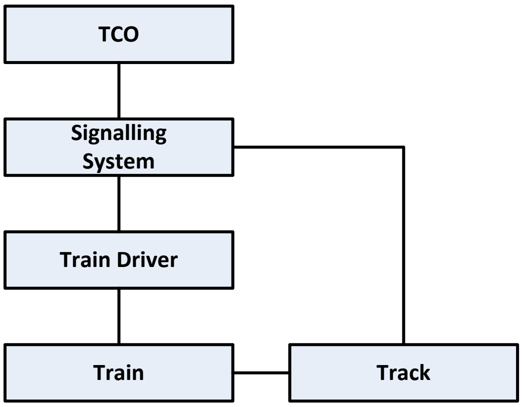


**Figure 5.1 System Structure – Generic CP Model**

Interface listing:

- TCO – Signalling System: Computer based control terminal
- Signalling System – Track: Train detection device (axle counter / track circuit)
- Signalling System – Train Driver: Signal lamp
- Train Driver – Train: Driver instrument panel
- Train – Track: Wheel on track

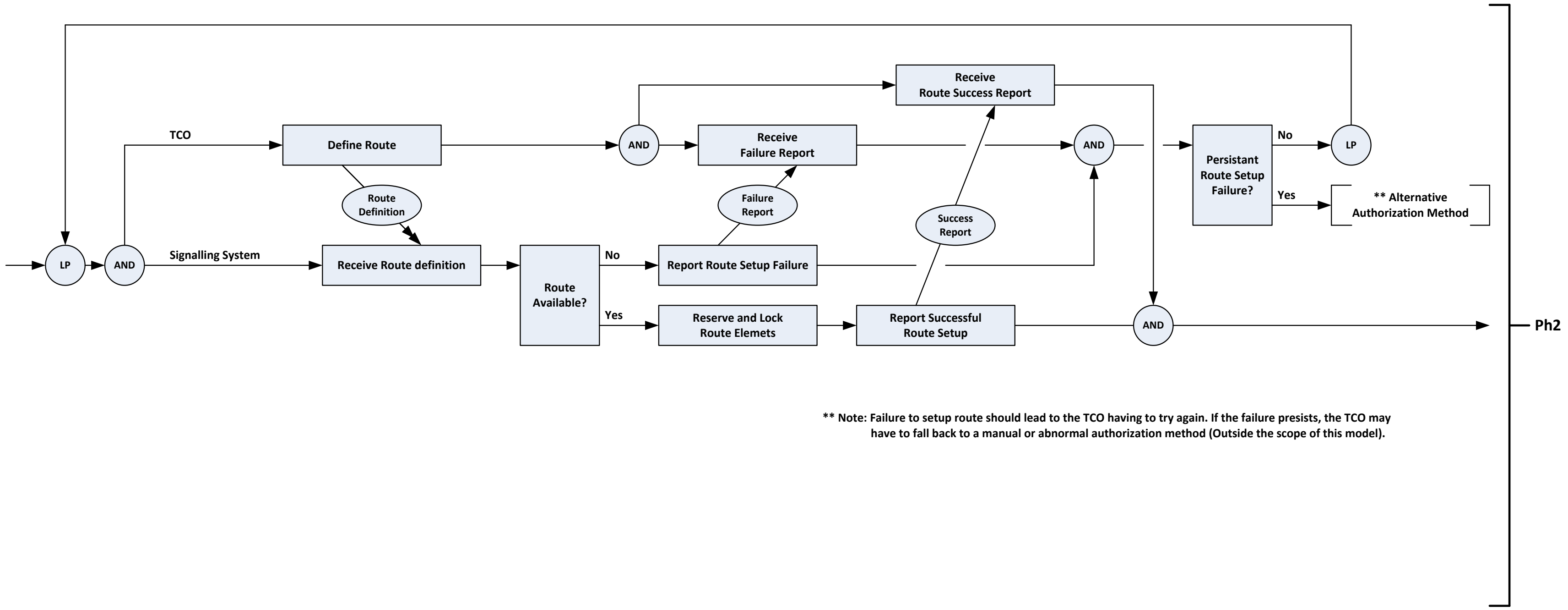


**Figure 5.2 System Behaviour Phase1 (Movement Setup) – Generic CP Model**

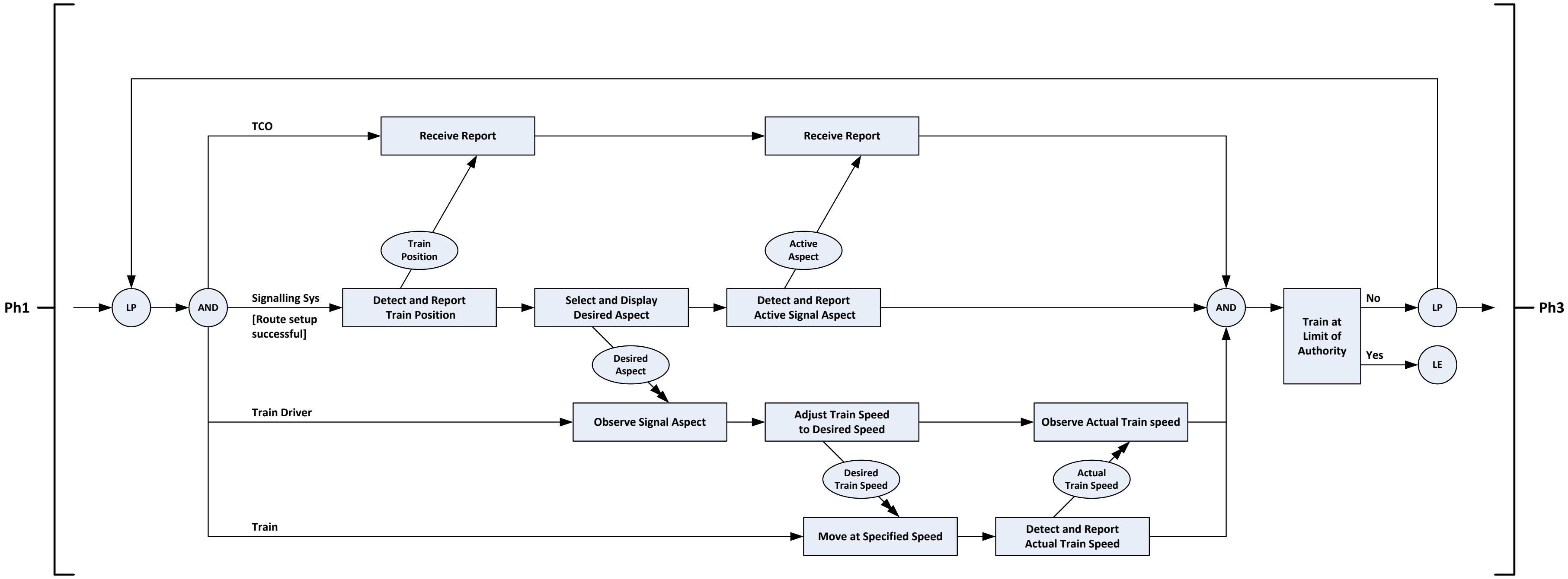


**Figure 5.3 System Behaviour Phase2 (Route Traversal) – Generic CP Model**

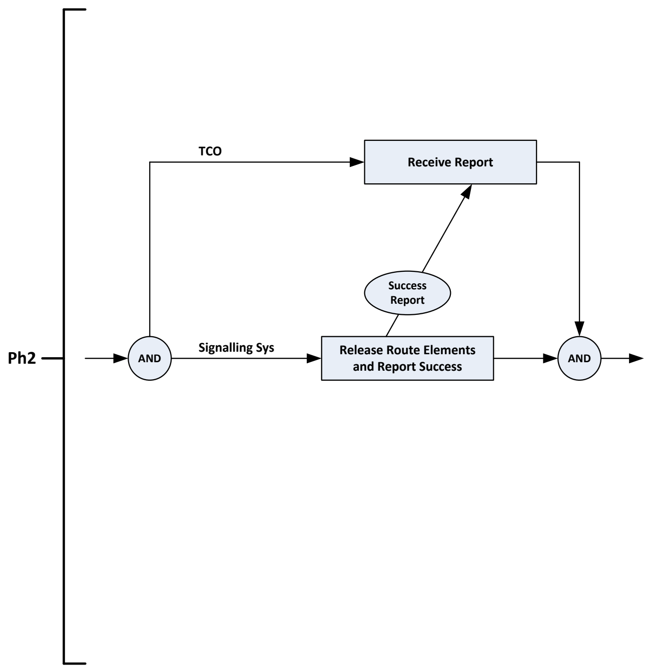


**Figure 5.4 System Behaviour Phase3 (End of Authority) – Generic CP Model**

## 5.2 PROPOSED AUTOMATION MODEL

There is also a large degree of commonality between the Proposed Automation models generated by ENG1 and ENG2. Both engineers based their models on Automatic Train Protection systems that intervene when the driver exceeds the required speed profiles. Both engineers also required their systems to police driving behaviour in order to promote efficient driving.

As with the Current Practice models, it should again be noted that if the level of detail of the models generated by ENG2 is reduced to the signalling system level and not the system component level, the differences between the Proposed Automation models for the Fully Signalled and Track Warrant operations are also reduced to simple differences in technology and not methodology. The resulting generic model, if presented on the signalling system level of detail, will therefore apply to both Fully Signalled and Track Warrant operations. This view together with the resulting model presented below (generic PA model) was confirmed in the ENG3 interview (modifications indicated in blue):

- Structure (Figure 5.5)
- Phase1 – Movement Setup (Figure 5.6)
- Phase2 – Route Traversal (Figure 5.7)
- Phase3 – End of Authority (Figure 5.8)

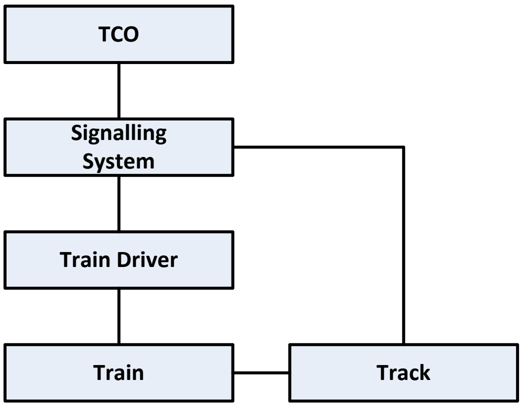


**Figure 5.5 System Structure – Generic PA Model**

Interface listing:

- TCO – Signalling System: Computer based control terminal
- Signalling System – Track: Train detection device (axle counter / track circuit)
- Signalling System – Train Driver: Signal lamp
- Train Driver – Train: Driver instrument panel
- Train – Track: Wheel on track

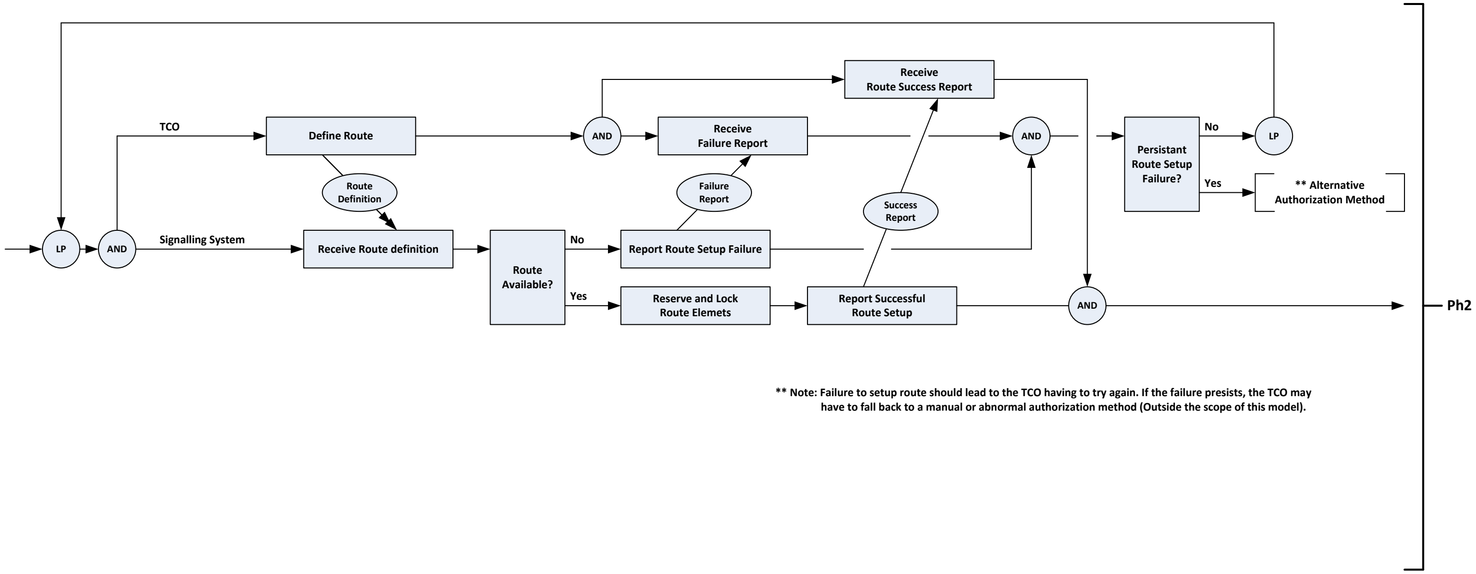


**Figure 5.6 System Behaviour Phase1 (Movement Setup) – Generic PA Model**

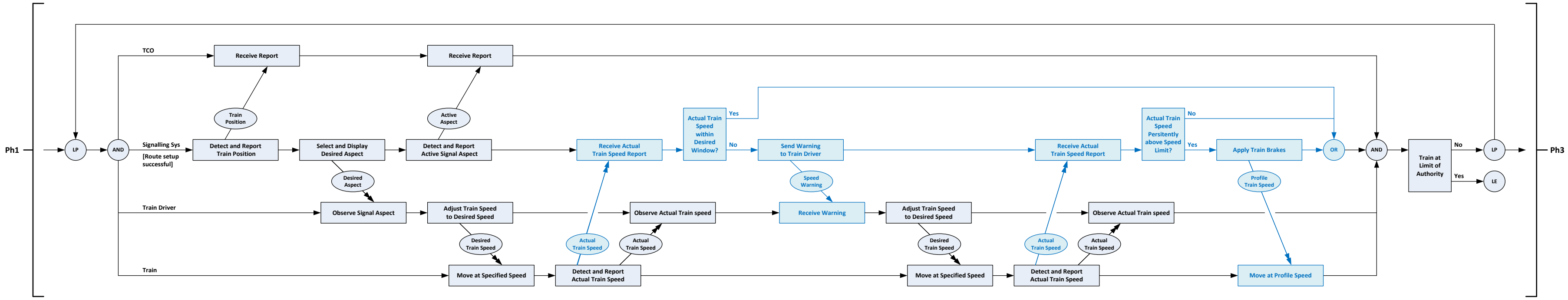


**Figure 5.7 System Behaviour Phase2 (Route Traversal) – Generic PA Model**

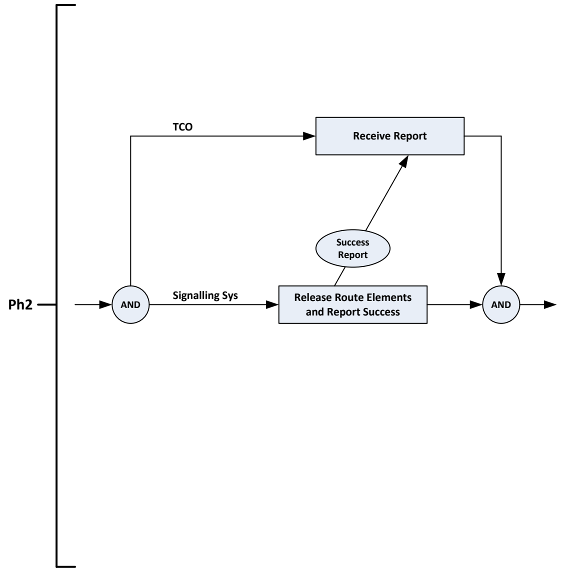


**Figure 5.8 System Behaviour Phase3 (End of Authority) – Generic PA Model**

# 6 DISCUSSION

This chapter will briefly discuss how the project met its defined objectives in an effort to answer the research question. This includes a discussion on how the results compared with the literature, how project objectives were met, if the problem under investigation was solved and if the research question was effectively answered.

Firstly, the resulting automation model confirmed the recommendations presented by the literature review as the modifications introduced were based on ATP systems consisting of a technical safety system that monitors driver behaviour and automatically intervenes in unsafe circumstances. Such systems are equivalent the automation level (Level1 - manual driving with technical supervision) - presented by the literature as the most appropriate method.

All of the defined research objectives were successfully met in the following ways:

A conceptualization of TFR signalling practices was developed from consultations with experienced signalling engineers and a review of the available technical literature. The result was also reviewed and endorsed by one of the interviewed signalling engineers.
In-depth, semi-structured interviews with signalling engineers were used to generate a model representative of the current practice within TFR in train movement authorization. All models were developed using a credible methodology, utilizing modelling languages and concepts that are well known within the system engineering community. The resulting model was endorsed as accurate by all of the signalling engineers interviewed.

The interviewees were also required to generate a proposed ideal automation model that would be effective in mitigating SPADS and that could be considered the most appropriate within the TFR environment. The resulting model was endorsed by all of the signalling engineers interviewed.

As a final test of the proposed automation model satisfied that critical research question, all of the interviewed signalling engineers were asked the following verifying questions:

- Do you agree with the recommendations from the literature review and if those recommendations were faithfully implemented in the proposed automation model?

- Would the resulting automation model be effective in mitigating SPADs and would you consider it to be the most appropriate train driver automation method for the TFR environment?

All of the interviewed signalling engineers answered in the affirmative.

In conclusion it can be stated that the resulting automation model effectively answered the research question in defining the most appropriate train driver automation model to mitigate SPADs in the TFR environment.

# 7 CONCLUSION AND RECOMMENDATIONS FOR FURTHER STUDY

Operator automation is a field that presents enormous potential advantages when it comes to the technological augmentation of human capabilities, yet it comes with significant engineering challenges as well. As has been evident in this study, this statement also holds true when considering the automation of the train driver within the TFR environment. At first glance, the completely automatic control of a train seems to be the simplest thing in the world yet when you step back and consider train control within the greater context of railway operation (the systems engineer's view), there are significant challenges that become apparent.

A thorough review of the literature has shown that human train driver errors and violations significantly contribute as causes of SPADs (a fundamental failure in driving safety) yet it has also been shown that the additional roles and functions fulfilled by a human train driver (i.e. intervention and support under abnormal circumstances) are not as easily automated. The most practical and readily available train driver automation model, mitigating most of the costs imposed by human failure associated with SPAD events yet retaining the value of human flexibility, was demonstrated to be that of retaining the human driver yet with technical supervision. In this arrangement, the human driver would remain in his conventional role of driving the train but with a technical supervision system superimposed that automatically intervenes if a train driver exceeds his movement authority. In addition, such a system could be tailored to also guide the driver towards optimal driving profiles.

The recommendations from the literature as well as the resulting generic model were wholeheartedly endorsed by the signalling engineers interviewed, affirming it met the requirements set out by the research question: That of being the most appropriate method of train driver function automation to mitigate SPADs in the TFR railway environment.

## 7.1 RECOMMENDATIONS FOR FURTHER STUDY

The financial costs typically attached to the safety systems and technologies such as Automatic Train Protection (ATP) can be significant and often prohibitive for large scale implementation and support in third world countries such as South Africa. In many cases (e.g. rural lines that carry predominantly freight traffic) the traffic densities and potential risk levels may not justify the costs associated with equipment carrying the Safety Integrity Level (SIL) ratings of SIL3 or SIL4 (BSI, 1999), typically associated with the high traffic density on metro lines. In such cases, the application of SIL1 or SIL2 systems may be sufficient if combined with soft strategies like the informal driver strategies presented by Naweed et al. (2015). The formalization and scientific evaluation of the effects on risk reduction of such strategies and initiatives, may prove a fruitful field for further study.

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# 9 APPENDIX

This appendix section forms part of the research report:

**Title:**

Train Driver Automation Strategies to Mitigate Signals Passed at Danger on South African Railways

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**Date:** 2018/04/18

## 9.1 ENG1 INTERVIEW DATA (RAW)

This appendix presents the raw data gathered from the interview with ENG1 (real name masked). Interview data includes a rundown of interview activities and interview findings covering pre-modelling discussion points, generated models and concluding remarks.

### 9.1.1 Interview execution

During the interview, the following actions were performed:

i. ENG1 reviewed and signed consent letter. Permission letter from TFR was made available for review if required.
ii. ENG1 and interviewer reviewed and discussed the literature review findings and theoretical basis for the project approach. The review covered the following (see attached info sheet):

   a. Research question
   b. The appropriateness of TFR as the subject of this study
   c. Typical causes of SPADs
   d. SPADs within TFR
   e. Selected train driver automation framework

f. Fundamental challenges to operator automation including the ironies of automation and the hidden roles of the train driver.
g. Review of the conclusion and motivation for the selection of Automation Level 1 (manual driving with technical supervision) as the most appropriate model of train driver automation to mitigate SPADs in the TFR environment.

iii. Introduction to the selected modelling method and language. Models should at least describe system structure and system behaviour.
iv. Initial modelling of system, describing how a rail movement authorization translates into an actual movement with emphasis on the role of the train driver.
v. ENG1 was presented the hypothesis confirmation / rejection questions

### 9.1.2 Interview findings: Pre-modelling discussion

The following findings were recorded as part of the pre-modelling discussion:

- ENG1 accepted and agreed with the conclusions presented by the literature review stating that the most appropriate model within the given framework should be based on Automatic Train Protection (ATP). At a first glance, ENG1 felt that the system should only intervene in cases where the speed limit is exceeded and also only when approaching danger signals (the minimum required to meet the safety goals) but stated that a system that guides the driver towards optimal driving patterns would be a great advantage. ENG1 emphasized that, from his observations and experience during his career in the SA railway industry, “malicious driver behaviour” is a major problem in South African railway operations. He described an example of such behaviour as where drivers would be driving especially slowly in order to be able to claim over-time. The desired system should therefore guide the driver towards the optimal speed profiles, probably taking the form of a target speed window for the driver to conform to, and if violated, then a real-time warning to the driver as well as capturing detail of each incident to record and subsequently remedy noncompliant driver behaviour Similar approaches to discouraging other driver behaviour that is not optimal should also be possible.

- To properly model TFR operations, the following typical modes or operational use-cases were identified for modelling:
    - Fully fledged signaled operation
    - Track warrant operation

  ENG1 did agree and accept the case that track warrant operations may not justify driver automation safety augmentation systems for the following reasons:
    - The fact that track warrant operation is only practiced on lines with very low traffic densities – low safety risk

    - The fact that these lines did not justify the implementation of conventional signalling systems to augment safety and do therefore not justify or require further safety augmentation.

  This reasoning resulted in the decision that track warrant not be considered for driver automation systems.

- ENG1 felt that the models do not have to differentiate between the roles of sub-components within the signalling system (eg. remote control, interlocking, signals, points, vacancy detection, etc) but can rather describe the functions and behaviour of the signalling system as a whole. This should simplify the drawings considerably.

- ENG1 felt that the implementation of the proposed ideal system should meet the following requirements:
    - The system should apply to movements, both in-station and in-section.
    - That the driver should not have the ability to override the safety system
    - That an optimal speed profile capability be included
    - That is must be installable on most locomotives.

- As it became evident that the modelling effort could take some time, ENG1 requested that the interviewer continue preparing these models and present them for review. The main features and flavour of the models were discussed and the interview session concluded.

- Other observations:
    - ENG1 remarked that the relatively low number of SPAD incidents reported on the British lines may only reflect the fact that ATP or similar systems may be the rule. The remaining incidents may then be a reflection of non-driver causes of SPADS such as technical problems. This may be a worthwhile question to investigate further.

    - On the point of challenging and varying train handling dynamics, ENG1 remarked that one of the most pronounced differences in handling dynamics come into play when comparing fully loaded trains vs empty trains. These differences recommend different driving approaches or driving styles.

#### 9.1.3 Interview findings: fully fledged signalling models

These models attempt to describe the full extent of the cycle associated with a train movement on a fully fledged signalled network: The setup of the route, the traversal of the train through the route, the arrival at the limit of authority culminating in the route behind the stationary trains having been normalized (see figure below). No point sets have been included for the purpose of simplification.

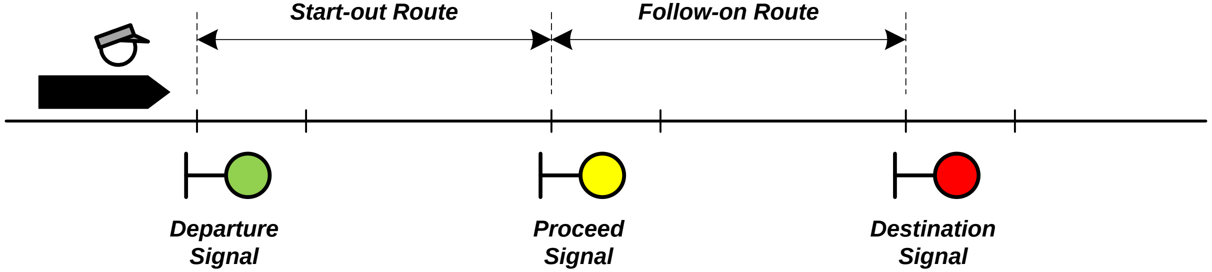


**Figure 9.1  Train movement**

**[Current Practice] System Structure**

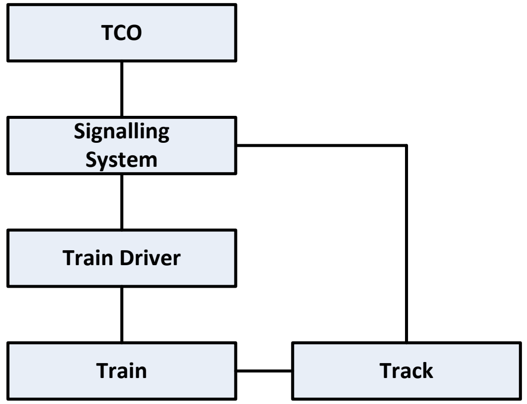


**Figure 9.2 System Structure**

## [Current Practice] System Behaviour – Phase1 (Movement Setup)

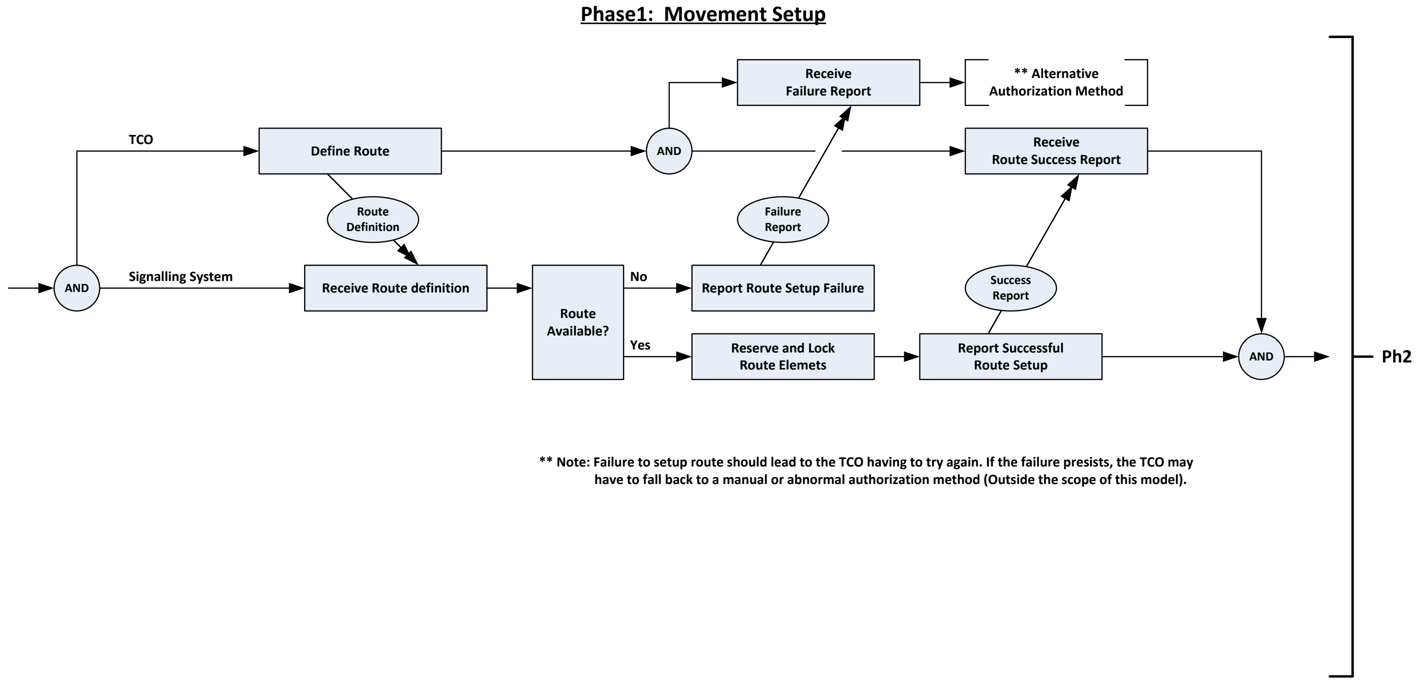


**Figure 9.3 System Behaviour - Phase1 (Movement Setup)**

## [Current Practice] System Behaviour – Phase2 (Route Traversal)

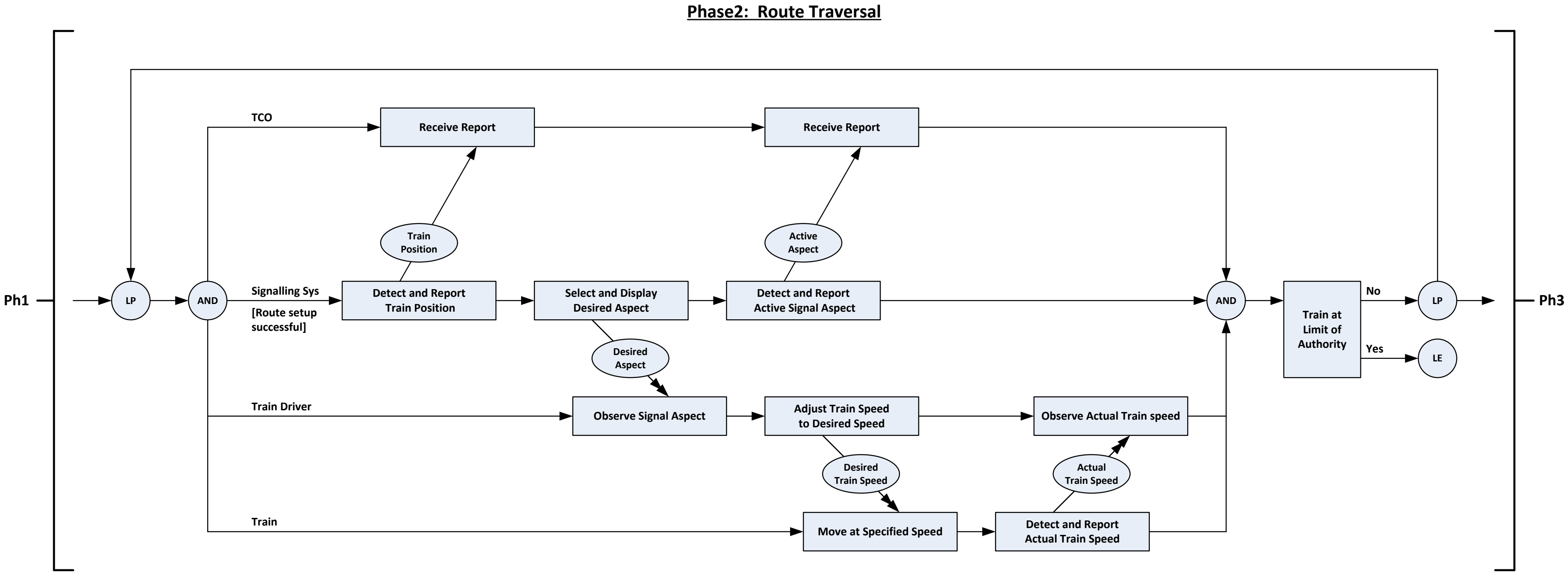


Figure 9.4 System Behaviour - Phase2 (Route Traversal)

## [Current Practice] System Behaviour – Phase3 (End of Authority)

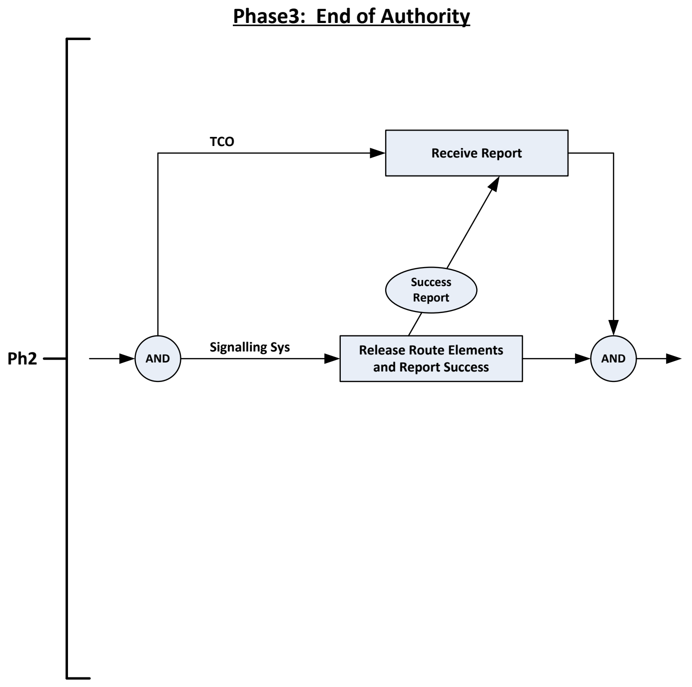


**Figure 9.5 System Behaviour - Phase3 (End of Authority)**

The modification introduced in the proposed ideal model is indicated in **BLUE**. The proposed ideal model also illustrates specifically what would happen if a driver fails to keep to the required speed limits.

**[Proposed Ideal] System Structure**

The structure for the proposed ideal system remains the same as that of the current practice.

**[Proposed Ideal] System Behaviour – Phase1 (Movement Setup)**

The Phase1 behaviour for the proposed ideal system remains the same as that of the current practice.

# [Proposed Ideal] System Behaviour – Phase2 (Route Traversal)

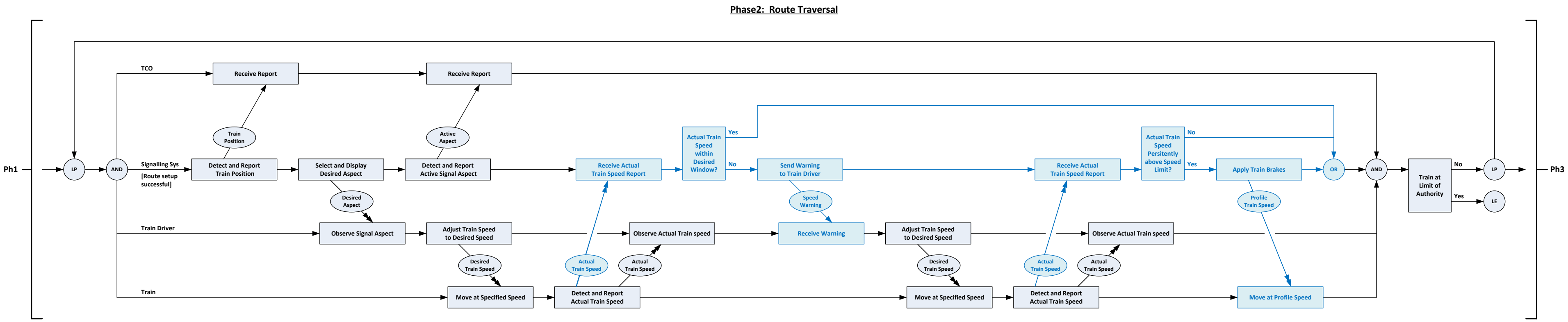


**Figure 9.6 System Behaviour - Phase2 (Route Traversal) [Proposed ideal]**

**[Current Practice] System Behaviour – Phase3 (End of Authority)**

The Phase3 behaviour for the proposed ideal system remains the same as that of the current practice.

### 9.1.4 Interview findings: concluding remarks

ENG1 was posed the following questions regarding the proposed ideal model developed: **[ENG1's answers in brackets]**

- Was the train driver function automation method recommended by the literature review implemented in the proposed ideal model? **[Yes]**
  - Firstly, Level 1 automation (manual driving with technical supervision) is the recommended automation model to be implemented. It should be noted that, to improve the practicability of the new model in the TFR railway environment, the model should be based on the current signalling and operational practices within TFR.

  - Secondly, the formal countermeasures and informal strategies presented by Naweed et al. (2015) align fairly well with the two elements that make up the CENELEC concept of risk (BSI, 1999). The informal strategies and vigilance improvement systems attempt to reduce driver error rates while intervention systems minimize the effects if driver errors were made. Although it is desirable to try and reduce the probability of train driver error, the methods seem to be somewhat open-ended as they cannot enforce safety. It does not mean that such methods are ineffective and should not be investigated or implemented but it can be argued that they do not present a solid foundation for

safety control. Reduction in the consequences seems to be the low hanging fruit in this case as it closes the loop in terms of safety enforcement (the result is forced) and is based on technologies that are well established and well understood. These systems (i.e. Automatic Train Protection and others) are based on the monitoring of human driver practice and enforcing safety by applying the brakes if the driver significantly exceeds the required speed restrictions or movement authorities. In many ways, such an approach constitutes having all of the advantages of using human train drivers, which has been shown to be considerable, while mitigating the disadvantages. It is therefore recommended to formulate and apply the new model along similar lines to ATP systems.

  - Thirdly, it may be worthwhile to consider adding functions that aid the driver in achieving better driving practice, but such functions should not form the basis of safety.

- Should this method prove effective in the mitigation of SPADs? **[Yes]**

- Can this model be considered as the ‘most appropriate’ within TFR railway operations? **[Yes]**

## 9.2 ENG2 INTERVIEW DATA (RAW)

This appendix presents the raw data gathered from the interview with ENG2 (real name masked). Interview data includes a rundown of interview activities and interview findings covering pre-modelling discussion points, generated models and concluding remarks.

### 9.2.1 Interview execution

During the interview, the following actions were performed:

i. ENG2 reviewed and signed consent letter. Permission letter from TFR was made available for review if required.
ii. ENG2 and interviewer reviewed and discussed the literature review findings and theoretical basis for the project approach. The review covered the following (see attached info sheet):

    a. Research question
    b. The appropriateness of TFR as the subject of this study
    c. Typical causes of SPADs
    d. SPADs within TFR
    e. Selected train driver automation framework

f. Fundamental challenges to operator automation including the ironies of automation and the hidden roles of the train driver.
g. Review of the conclusion and motivation for the selection of Automation Level 1 (manual driving with technical supervision) as the most appropriate model of train driver automation to mitigate SPADs in the TFR environment.

iii. Introduction to the selected modelling method and language. Models should at least describe system structure and system behaviour.
iv. Initial modelling of system, describing how a rail movement authorization translates into an actual movement with emphasis on the role of the train driver.
v. ENG2 was presented the hypothesis confirmation / rejection questions

### 9.2.2 Interview findings: Pre-modelling discussion

The following findings were recorded as part of the pre-modelling discussion:

- ENG2 accepted the and agreed with the conclusions presented by the literature review stating that the most appropriate model within the given framework should be based on Automatic Train Protection (ATP) and should include consequences for the driver in cases where the safety system was required to intervene.

- ENG2 emphasized the fact that any solution should not significantly impact the train working rules (the technology should follow the rules and not the rues the technology) and that the solution should prioritize safety above productivity.

- To properly model TFR operations the following the following modes or operational use-cases were identified for modelling:
    - Fully fledged signalled operation
    - Track warrant operation

- As it became evident that the modelling effort could take some time, ENG2 requested that the interviewer continue preparing these models and present them for review. The main features and flavour of the models were discussed and the interview session concluded.

- Other observations:
    - ENG2 made the point that the role of railway signalling is to create safe railway capacity – not only safety and not only capacity.

- ENG2 explained the following distinction between the following South African signalling conventions:
  - 3 aspect signalling:  Driver to respond to signal aspect as soon as he sees it (even before he arrives at the signal).
  - Multi-aspect signalling:  Driver to respond to signal aspect only when he arrived at the signal location.
  - Multiple-aspect signalling:  Driver to respond to signal aspect only when he arrived at the signal location.

- ENG2 mentioned that the new PRASA trains have the capability to implement full cab-signalling in the future.

- As we were discussing the difficulty of a monitor/driver that has not remained in practice to step in and effectively take control of a train, ENG2 emphasized the fact that this may even be more difficult on Distributed Power (DP) trains. DP trains are freight trains that use multiple locomotives distributed throughout the train length while being controlled by a single driver. Controls of such trains are notoriously difficult, even for experienced drivers.

- ENG2 mentioned but was not sure of the fact that the TFR CS90 system may include the feature of checking for conflicts while the TCO is issuing track warrants or performing manual authorizations.

### 9.2.3 Interview findings: fully fledged signalling models

These models attempt to describe the full life cycle associated with a train movement on a fully fledged signalled network: The setup of the route, the traversal of the train through the route, the arrival at the limit of authority culminating in the route being normalized (see figure below). For simplification purposes, no points sets are included.

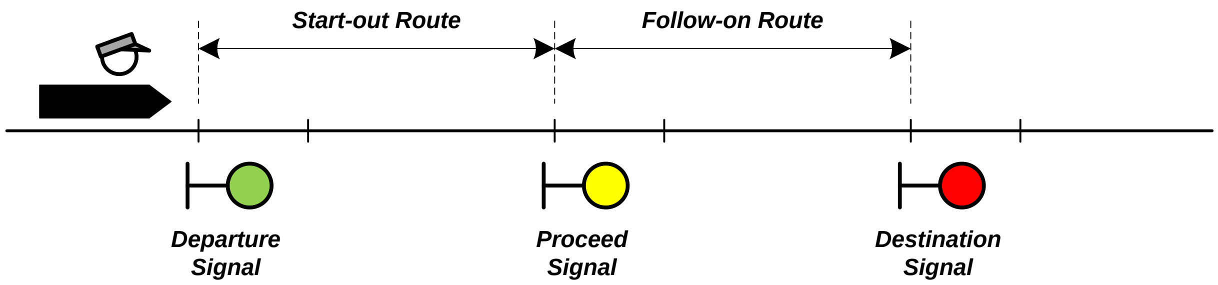


**Figure 9.7 Train movement**

**[Current Practice] System Structure**

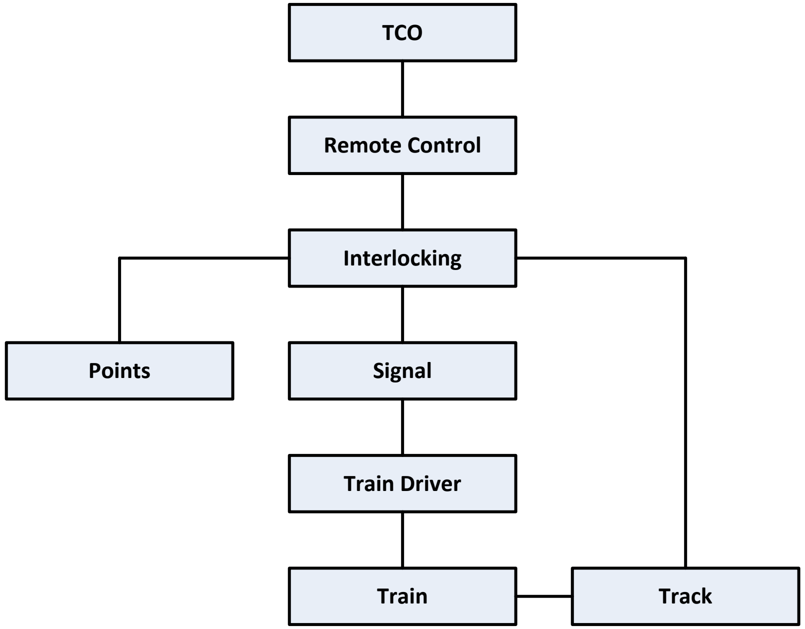


**Figure 9.8  System Structure**

## [Current Practice] System Behaviour – Phase1 (Movement Setup)

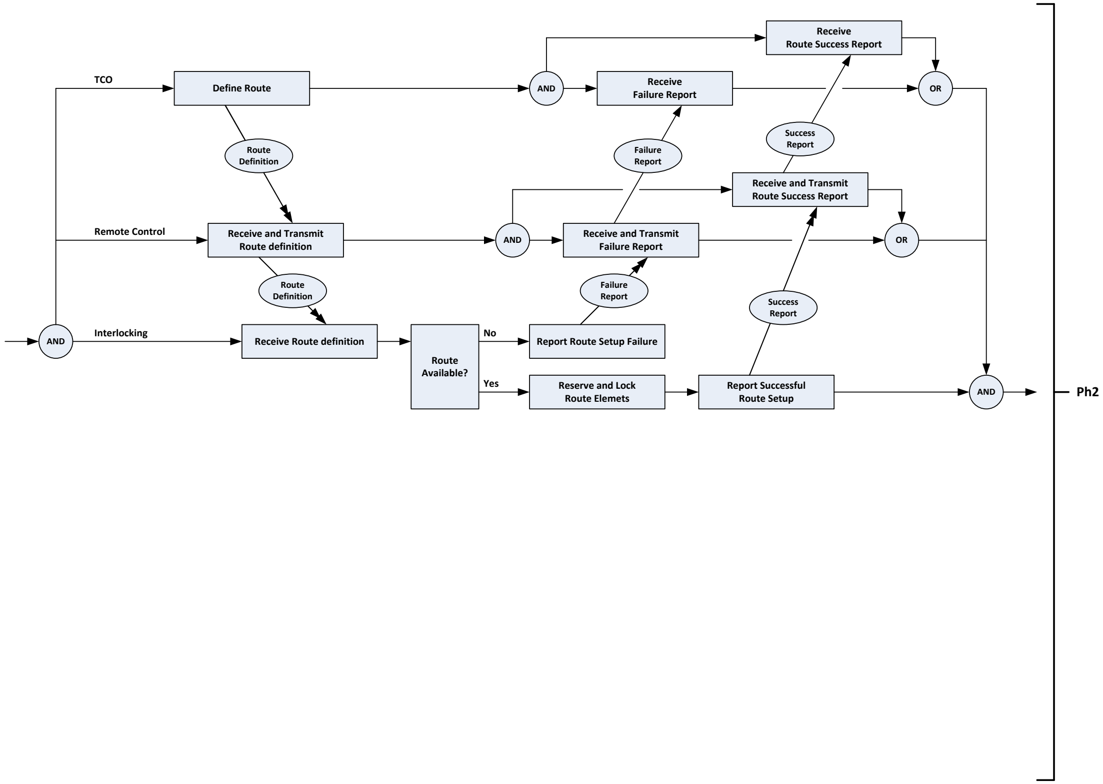


**Figure 9.9 System Behaviour - Phase1 (Movement Setup)**

## [Current Practice] System Behaviour – Phase2 (Route Traversal)

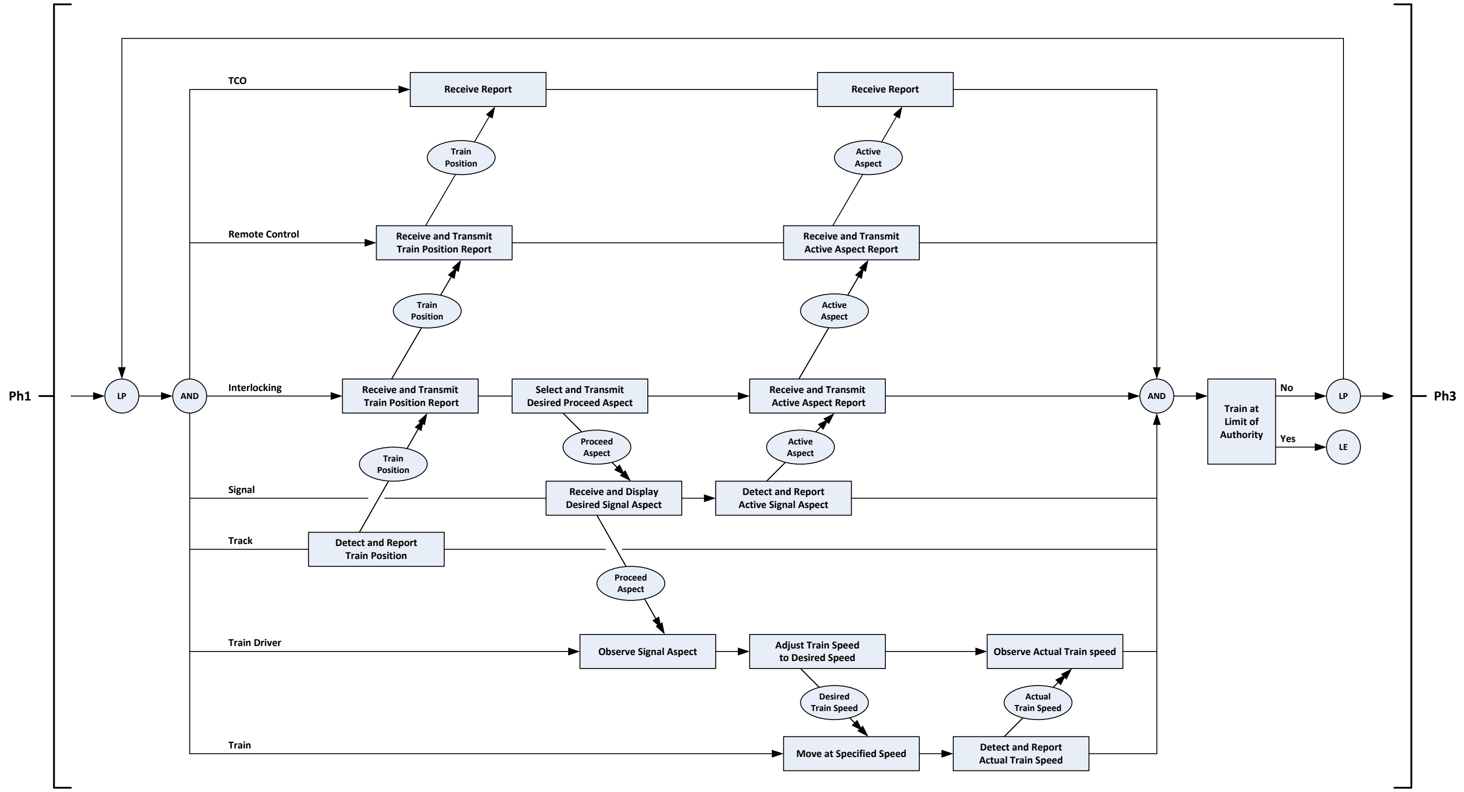


**Figure 9.10 System Behaviour - Phase2 (Route Traversal)**

## [Current Practice] System Behaviour – Phase3 (End of Authority)

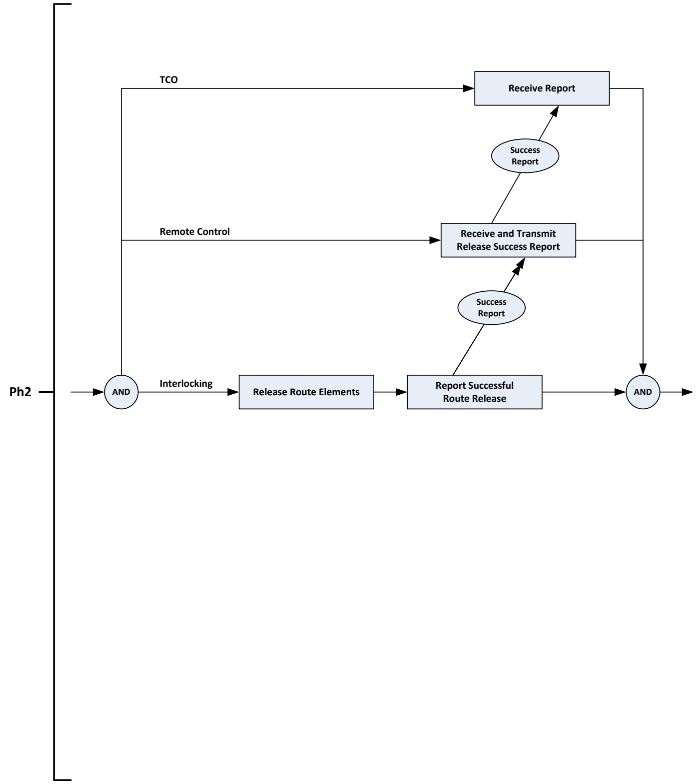


**Figure 9.11 System Behaviour - Phase3 (End of Authority)**

The modification introduced in the proposed ideal model is indicated in **BLUE**. Phase1 for the proposed ideal system behaviour is not indicated as it is the same as that of the current practice model. The proposed ideal model also illustrates specifically what would happen if a driver fails to keep to the required speed limits.

**[Proposed Ideal] System Structure**

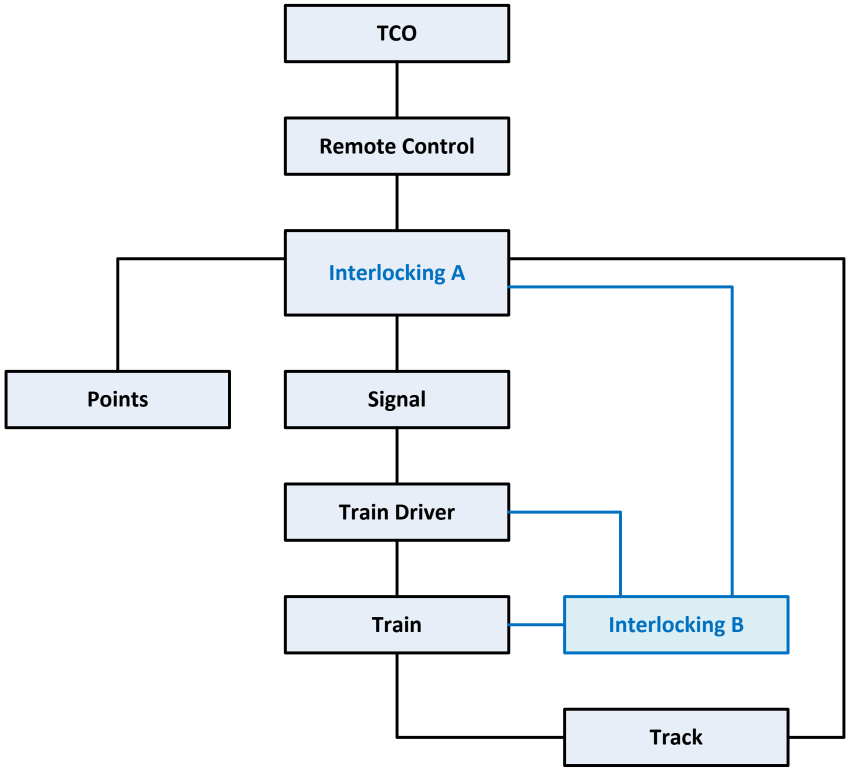


**Figure 9.12 System Structure [Proposed ideal]**

**[Proposed Ideal] System Behaviour – Phase1 (Movement Setup)**
The Phase1 behaviour for the proposed ideal system remains the same as that of the current practice.

## [Proposed Ideal] System Behaviour – Phase2 (Route Traversal)

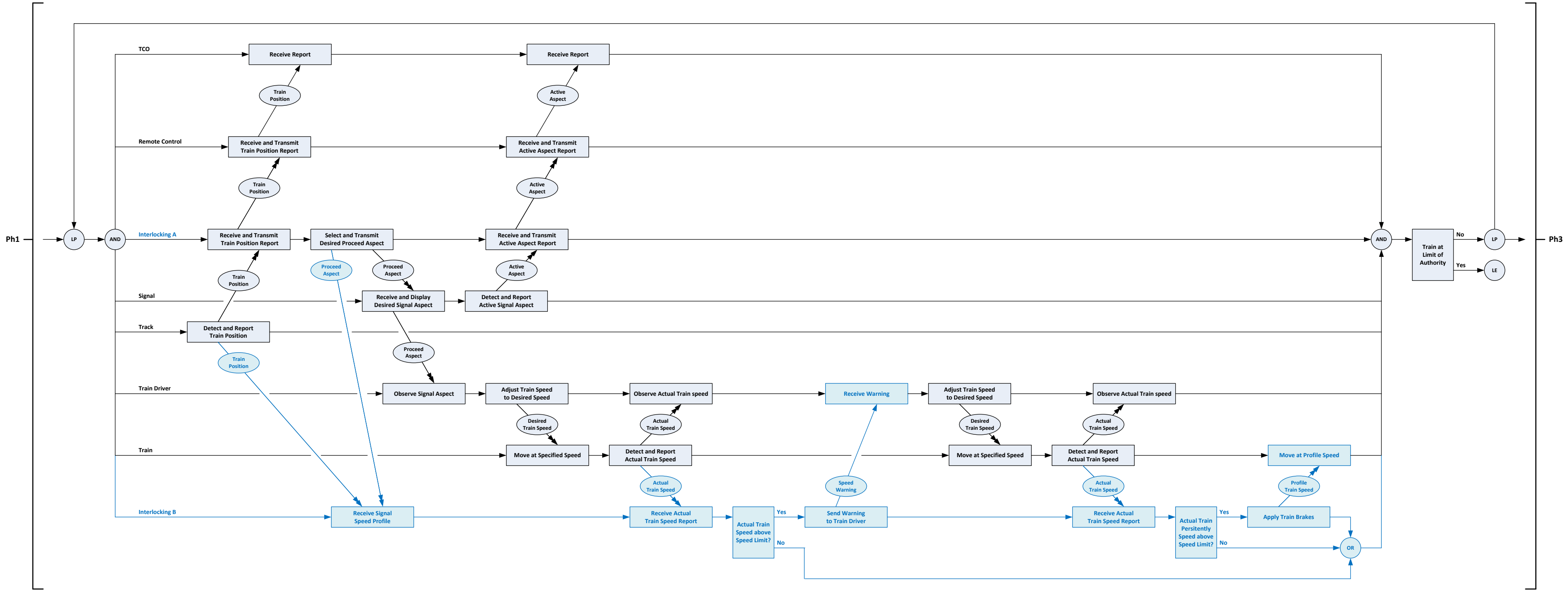


Figure 9.13 System Behaviour - Phase2 (Route Traversal) [Proposed ideal]

**[Proposed Ideal] System Behaviour – Phase3 (End of Authority)**

The Phase3 behaviour for the proposed ideal system remains the same as that of the current practice.

### 9.2.4 Interview findings: Track Warrant signalling models

These models attempt to describe the full life cycle associated with a train movement on a Track Warrant network: The setup of the route, the traversal of the train through the route, the arrival at the limit of authority (represented by a points) culminating in the route being normalized (see figure below).

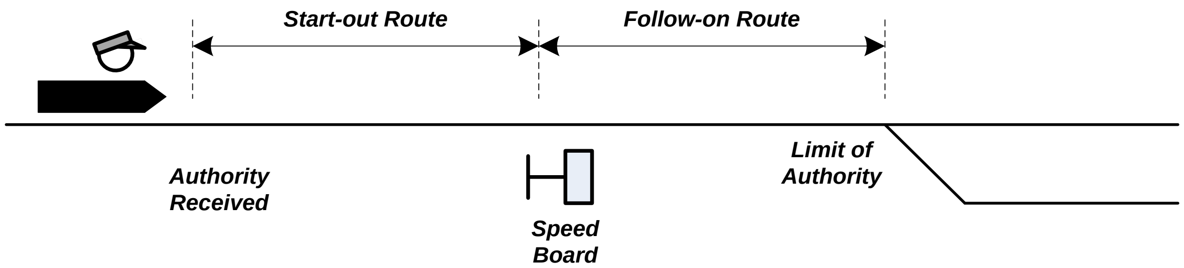


**Figure 9.14 Train movement**

## [Current Practice] System Structure

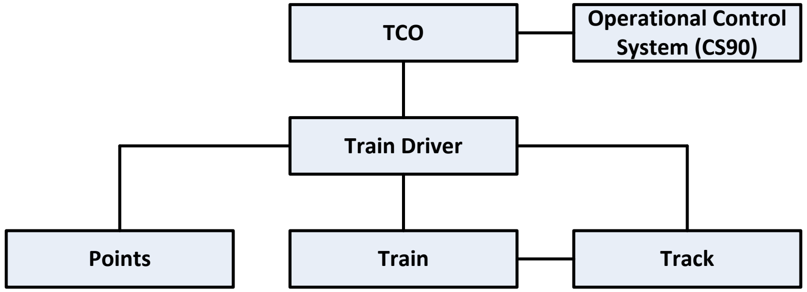


**Figure 9.15 System Structure**

## [Current Practice] System Behaviour – Phase1 (Movement Setup)

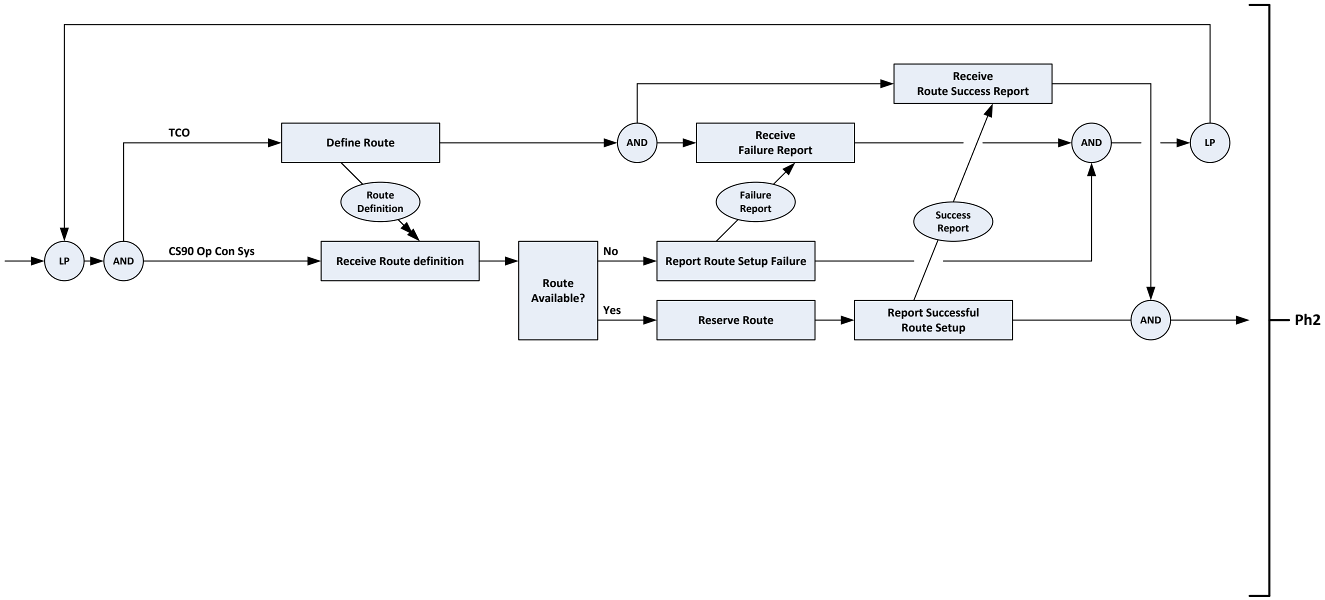


**Figure 9.16  System Behaviour - Phase1 (Movement Setup)**

## [Current Practice] System Behaviour – Phase2 (Route Traversal)

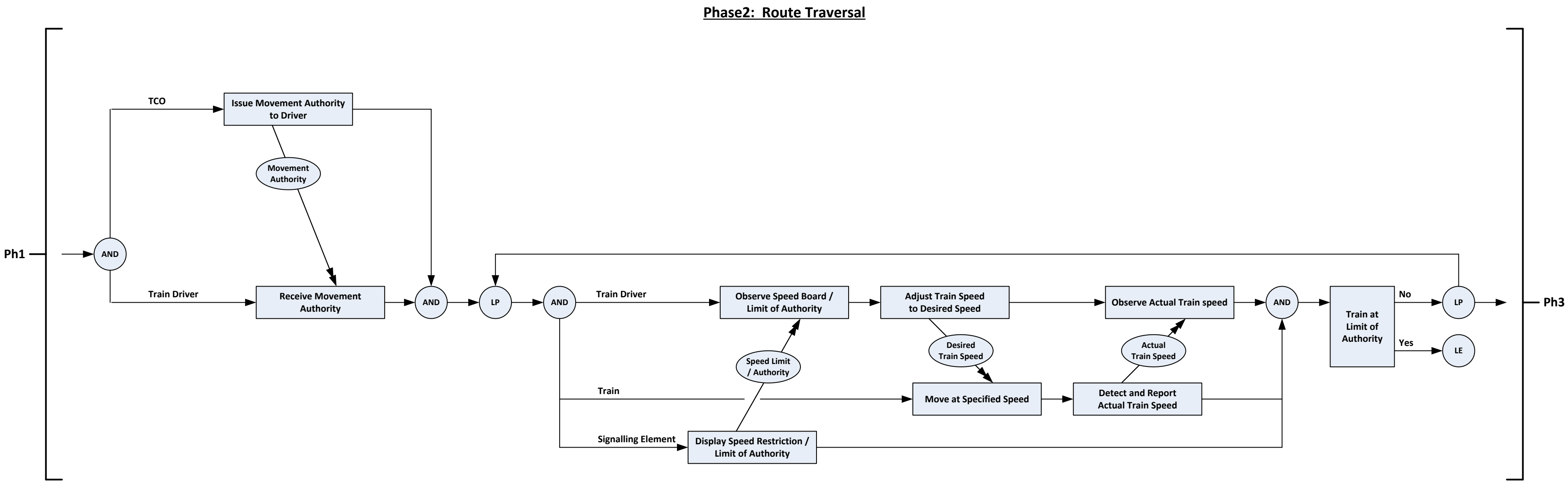


**Figure 9.17 System Behaviour - Phase2 (Route Traversal)**

## [Current Practice] System Behaviour – Phase3 (End of Authority)

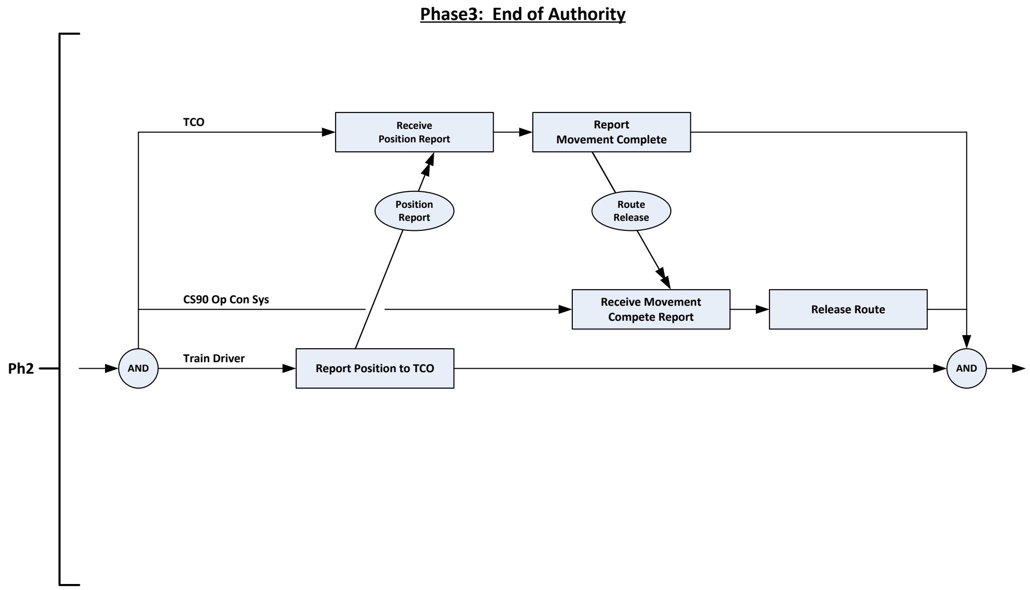


**Figure 9.18 System Behaviour - Phase3 (End of Authority)**

The modification introduced in the proposed ideal model is indicated in **BLUE**. The proposed ideal model also illustrates specifically what would happen if a driver fails to keep to the required speed limits.

**[Proposed Ideal] System Structure**

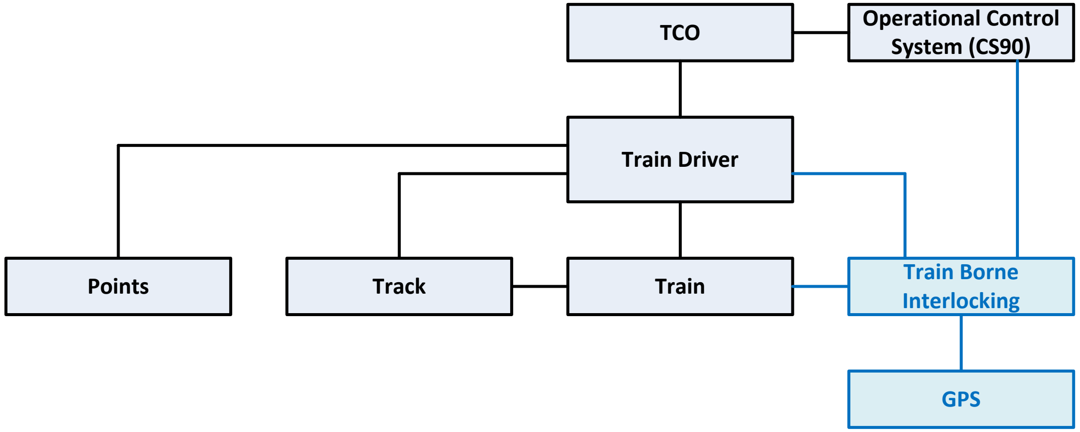


**Figure 9.19 System Structure [Proposed ideal]**

## [Proposed Ideal] System Behaviour – Phase1 (Movement Setup)

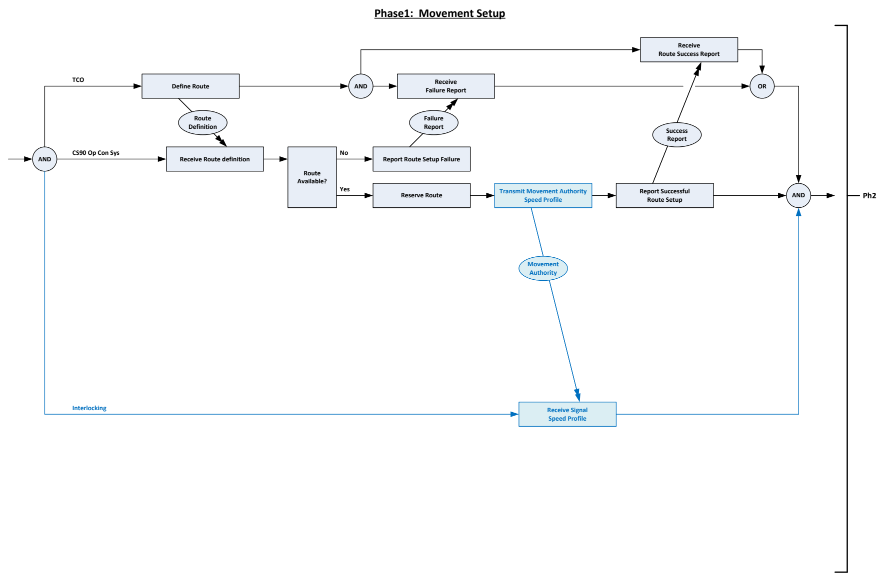


**Figure 9.20 System Behaviour - Phase1 (Movement Setup) [Proposed ideal]**

## [Proposed Ideal] System Behaviour – Phase2 (Route Traversal)

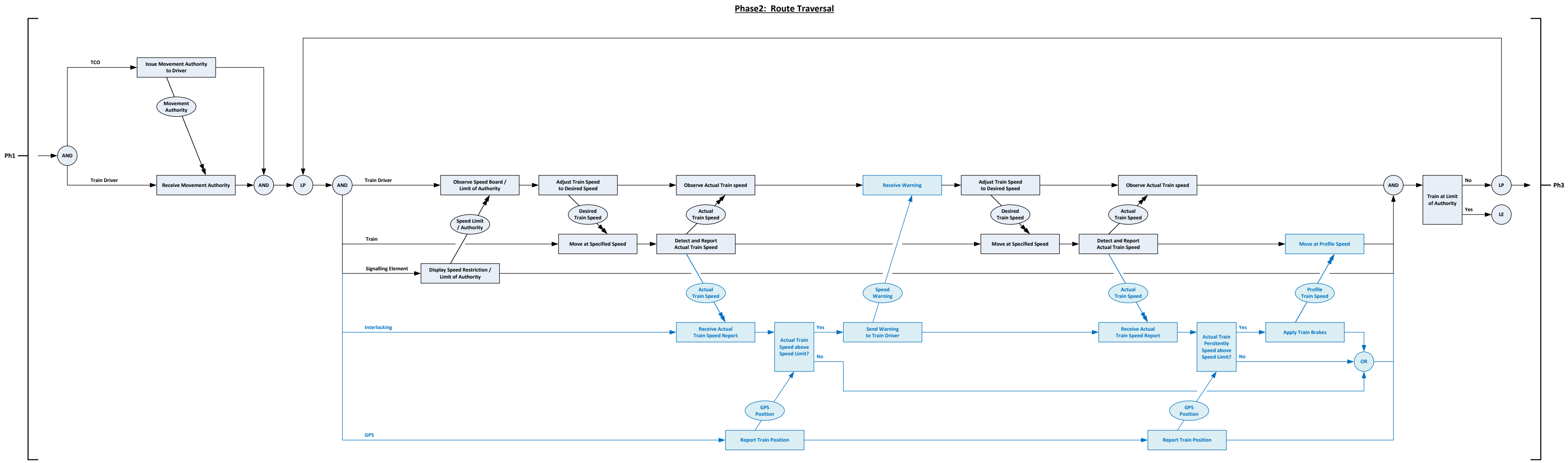


**Figure 9.21 System Behaviour - Phase2 (Route Traversal) [Proposed ideal]**

**[Current Practice] System Behaviour – Phase3 (End of Authority)**

The Phase3 behaviour for the proposed ideal system remains the same as that of the current practice.

### 9.2.5 Interview findings: concluding remarks

ENG2 was posed the following questions regarding the proposed ideal model developed: **[ENG2's answers in brackets]**

- Was the train driver function automation method recommended by the literature review implemented in the proposed ideal model? **[Yes]**
  - Firstly, Level 1 automation (manual driving with technical supervision) is the recommended automation model to be implemented. It should be noted that, to improve the practicability of the new model in the TFR railway environment, the model should be based on the current signalling and operational practices within TFR.

  - Secondly, the formal countermeasures and informal strategies presented by Naweed et al. (2015) align fairly well with the two elements that make up the CENELEC concept of risk (BSI, 1999). The informal strategies and vigilance improvement systems attempt to reduce driver error rates while intervention systems minimize the effects if driver errors were made. Although it is desirable to try and reduce the probability of train driver error, the methods seem to be somewhat open-ended as they cannot enforce safety. It does not mean that such methods are ineffective and should not be investigated or implemented but it can be argued that they do not present a solid foundation for

safety control. Reduction in the consequences seems to be the low hanging fruit in this case as it closes the loop in terms of safety enforcement (the result is forced) and is based on technologies that are well established and well understood. These systems (i.e. Automatic Train Protection and others) are based on the monitoring of human driver and enforcing safety by applying the brakes if the driver significantly exceeds the required speed restrictions or movement authorities. In many ways such an approach constitutes having all of the advantages of having a human train driver, which has been shown to be considerable, while mitigating the disadvantages. It is therefore recommended to model the new model along similar lines to ATP systems.

  - Thirdly, it may worthwhile to consider adding functions that aids the driver in better driving but such functions should not form the basis of safety.

- Should this method prove effective in the mitigation of SPADs? **[Yes]**

- Can this model be considered as the ‘most appropriate’ within TFR railway operations? **[Yes]**

## 9.3 ENG3 INTERVIEW DATA (RAW)

This appendix presents the raw data gathered from the interview with ENG3 (real name masked). Interview data includes a rundown of interview activities and interview findings covering pre-modelling discussion points, generated models and concluding remarks.

### 9.3.1 Interview execution

During the interview, the following actions were performed:

i. ENG3 reviewed and signed consent letter.
ii. ENG3 and interviewer reviewed and discussed the literature review findings and theoretical basis for the project approach. The review covered the following (see attached info sheet):

    a. Research question
    b. Typical causes of SPADs
    c. Selected train driver automation framework
    d. Fundamental challenges to operator automation including the ironies of automation and the hidden roles of the train driver.

e. Review of the conclusion and motivation for the selection of Automation Level 1 (manual driving with technical supervision) as the most appropriate model of train driver automation to mitigate SPADs in the TFR environment.

iii. The main conclusions, recommendations and models generated by ENG1 and ENG2 was presented to ENG3 for confirmation purposes and comment.

iv. ENG3 was presented with the hypothesis confirmation / rejection questions

### 9.3.2 Interview findings: Pre-modelling discussion

The following findings were recorded as part of the pre-modelling discussion:

- ENG3 accepted and agreed with the conclusions presented by the literature review, ENG1 and ENG2, stating that the most appropriate model within the given framework should be based on Automatic Train Protection (ATP) and that the inclusion of consequences for bad train driving is reasonable.

- ENG3 recommended that any system implementation should not clutter the train cab with screens that divert driver attention from watching the road but should aim to make the driving activity as easy as possible while leaving the driver in complete control of the train.

- ENG3 also recommended that from both a design and modelling point of view, the Remote Control system, as an interface between the TCO and the interlocking, should be as transparent as possible.

- When asked about the appropriate level of detail for the models, ENG3 did not indicate a specific preference, stating that the levels presented by both ENG1 and ENG2 were acceptable to him.

- Commenting on the current implementation of the VDU Warrant system where an train-borne On-Board Computer (OBC) system is used to perform safety interlocking functions in Track Warrant operations, ENG3 expressed the following concern:

  - The insufficient safety rating of the equipment used to perform safety functions (similar to those of an ATP system) may lead to safety incidents in the future. This is especially true in those cases where signalling information fed through a non-vital remote control is relied upon for train protection.

### 9.3.3 Interview findings: fully fledged as well as track warrant signalling models

These models attempt to describe the full life cycle associated with a train movement on a fully fledged signalled network (Figure 9.22) as well as a Track warrant network (Figure 9.23). The movement starts with the setup of the route, followed by the traversal of the train through the route and arrival at the limit of authority, culminating in the route being normalized. For the track warrant movement, the speed limit is communicated to the driver by a speed board and the limit of movement is indicated by the points set (see Figure 9.23).

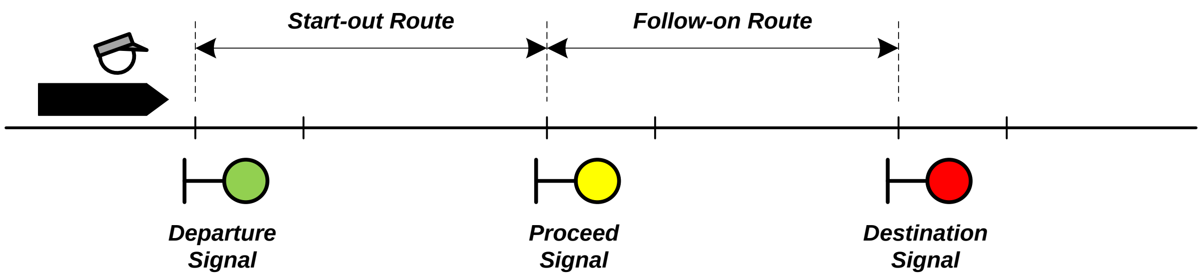


**Figure 9.22 Movement on Fully Fledged Signalled Network**

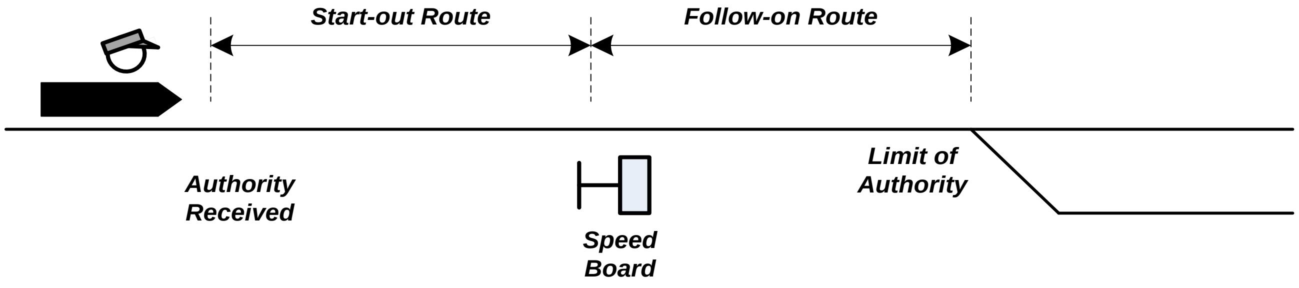


**Figure 9.23 Movement on Track Warrant Network**

When the modelling level of abstraction is set to the signalling system level instead of signalling system component level, the differences in structure and behaviour between that of the fully fledged signalling system and that of a Track Warrant system disappear, resulting in a generic model applicable to both modes of operation. Differences between the systems should only come into play when considering the actual implementation where the fully fledged signalling system may require a more safety conscious design and consist of components with higher safety ratings than that of the Track Warrant system.

**[Current Practice] System Structure**

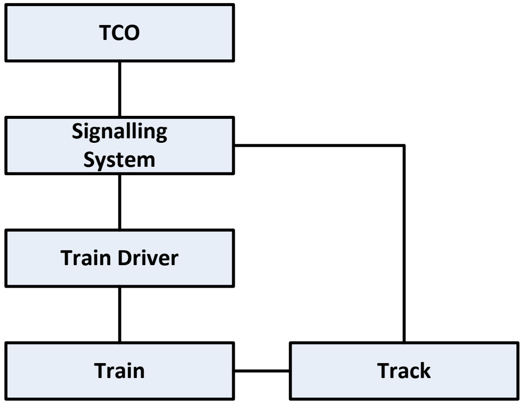


**Figure 9.24 System Structure**

## [Current Practice] System Behaviour – Phase1 (Movement Setup)

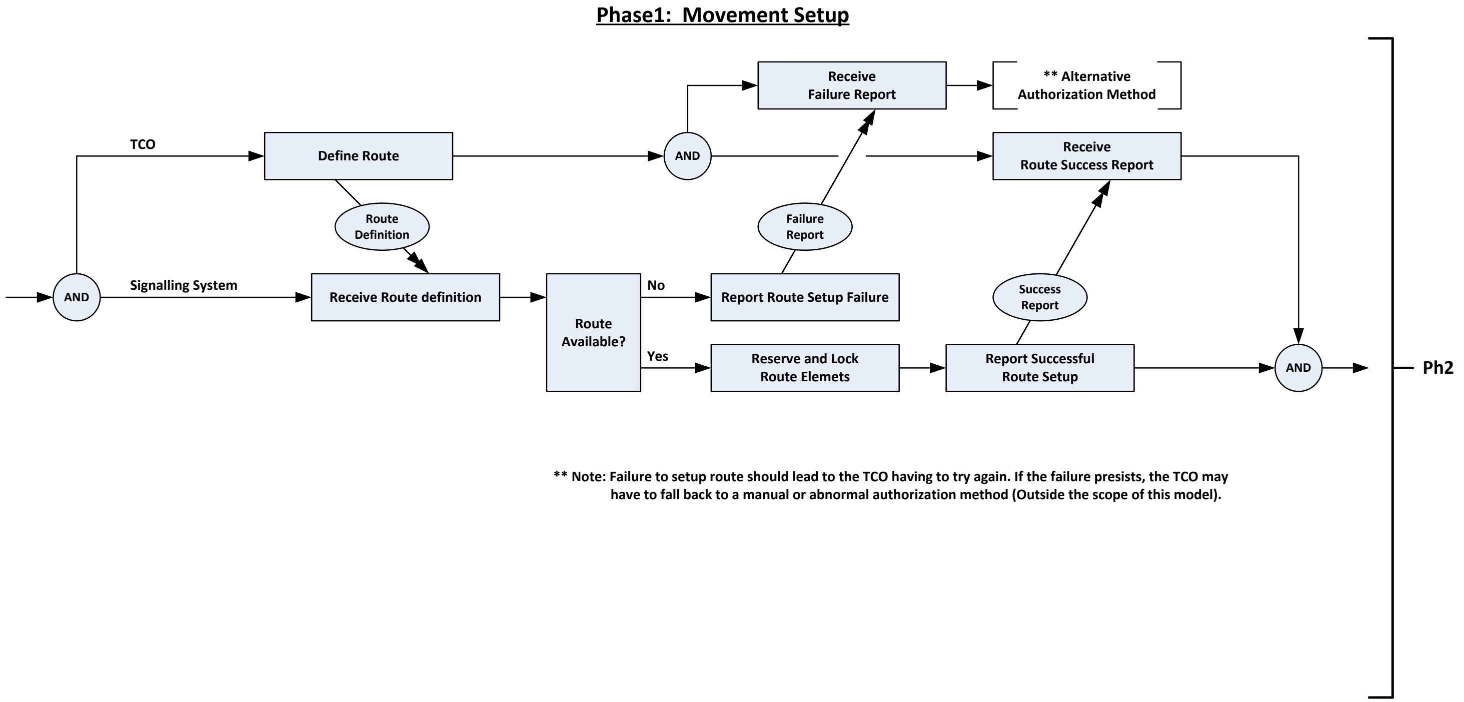


**Figure 9.25 System Behaviour - Phase1 (Movement Setup)**

## [Current Practice] System Behaviour – Phase2 (Route Traversal)

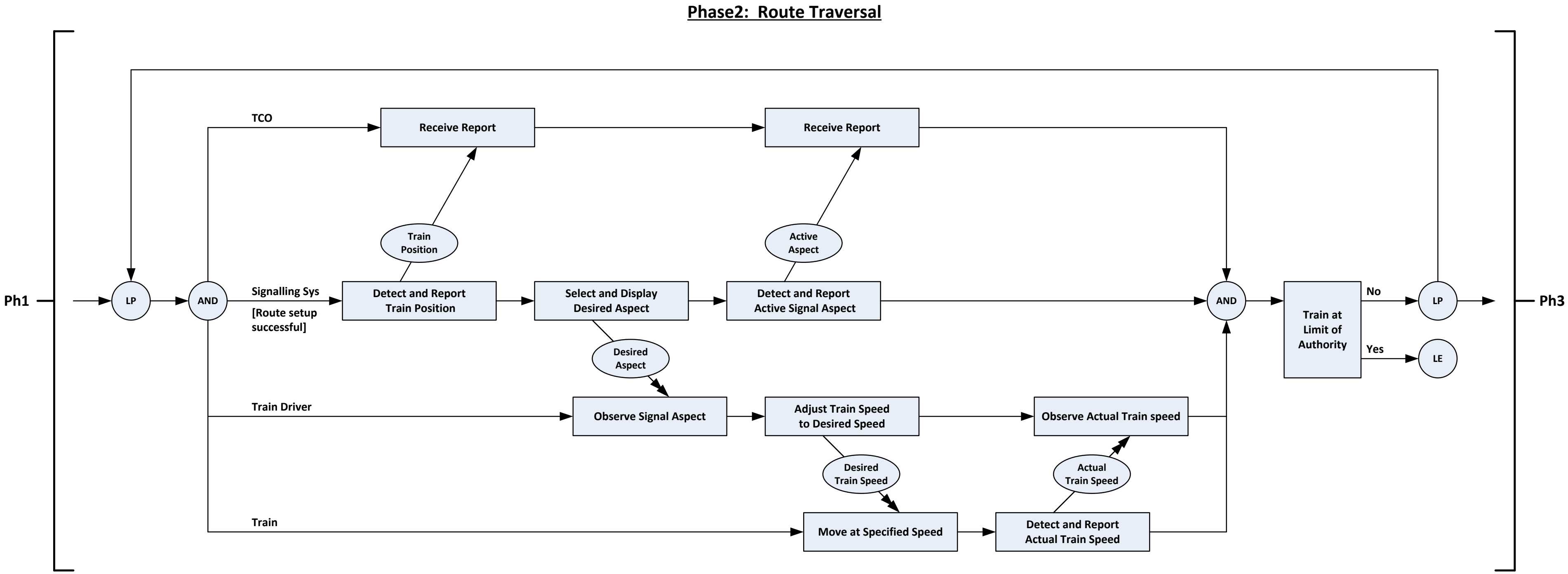


**Figure 9.26 System Behaviour - Phase2 (Route Traversal)**

## [Current Practice] System Behaviour – Phase3 (End of Authority)

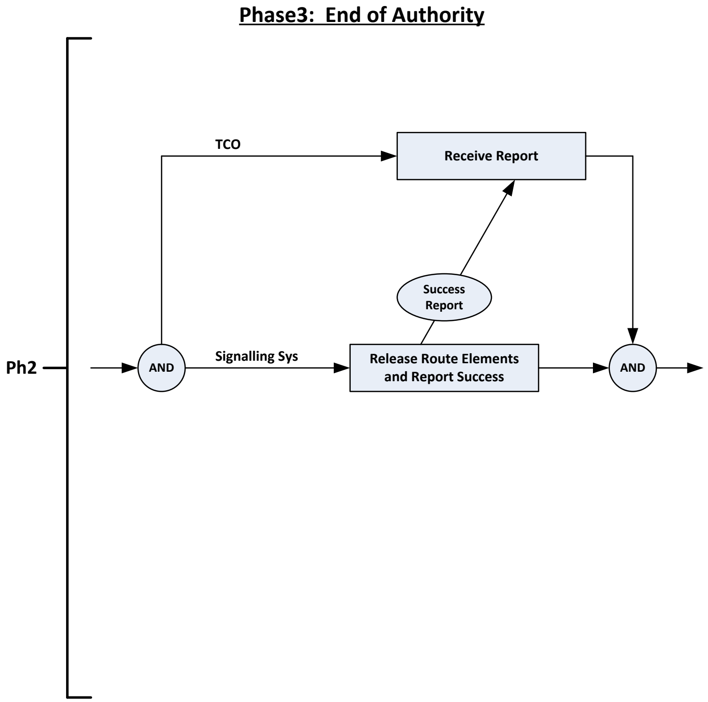


Figure 9.27 System Behaviour - Phase3 (End of Authority)

The modifications introduced in the proposed ideal model is indicated in **BLUE**. The proposed ideal model also illustrates specifically what would happen if a driver fails to keep to the required speed limits.

**[Proposed Ideal] System Structure**

The structure for the proposed ideal system remains the same as that of the current practice model.

**[Proposed Ideal] System Behaviour – Phase1 (Movement Setup)**

The Phase1 behaviour for the proposed ideal system remains the same as that of the current practice model.

## [Proposed Ideal] System Behaviour – Phase2 (Route Traversal)

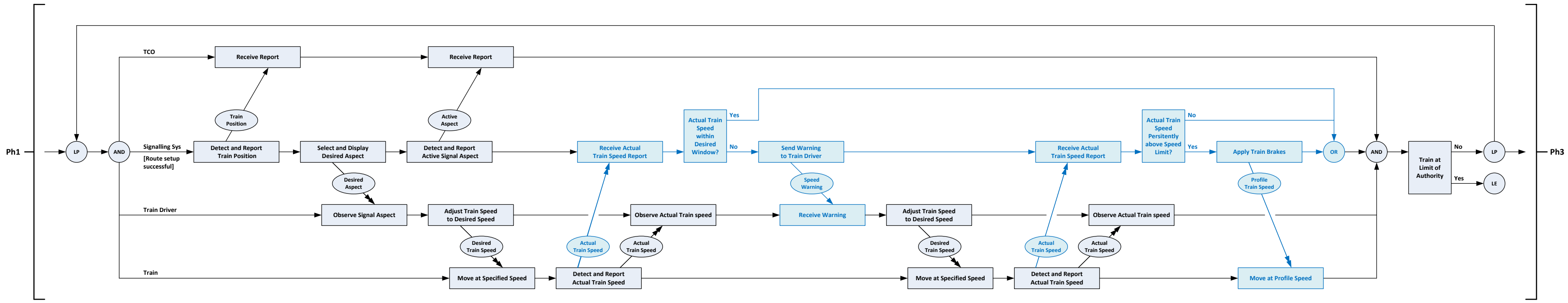

Figure 9.28  System Behaviour - Phase2 (Route Traversal) [Proposed ideal]

**[Proposed Ideal] System Behaviour – Phase3 (End of Authority)**

The Phase3 behaviour for the proposed ideal system remains the same as that of the current practice model.

### 9.3.4 Interview findings: concluding remarks

ENG3 was posed the following questions regarding the proposed ideal model developed: **[ENG3's answers in brackets]**

- Was the train driver function automation method recommended by the literature review implemented in the proposed ideal model? **[Yes]**
    - Firstly, Level 1 automation (manual driving with technical supervision) is the recommended automation model to be implemented. It should be noted that, to improve the practicability of the new model in the TFR railway environment, the model should be based on the current signalling and operational practices within TFR.

    - Secondly, the formal countermeasures and informal strategies presented by Naweed et al. (2015) align fairly well with the two elements that make up the CENELEC concept of risk (BSI, 1999). The informal strategies and vigilance improvement systems attempt to reduce driver error rates while intervention systems minimize the effects if driver errors were made. Although it is desirable to try and reduce the probability of train driver error, the methods seem to be somewhat open-ended as they cannot enforce safety. It does not mean that such methods are ineffective and should not be investigated or implemented but it can be argued that they do not present a solid foundation for

safety control. Reduction in the consequences seems to be the low hanging fruit in this case as it closes the loop in terms of safety enforcement (the result is forced) and is based on technologies that are well established and well understood. These systems (i.e. Automatic Train Protection and others) are based on the monitoring of human driver and enforcing safety by applying the brakes if the driver significantly exceeds the required speed restrictions or movement authorities. In many ways such an approach constitutes having all of the advantages of having a human train driver, which has been shown to be considerable, while mitigating the disadvantages. It is therefore recommended to model the new model along similar lines to ATP systems.

- Thirdly, it may worthwhile to consider adding functions that aids the driver in better driving but such functions should not form the basis of safety.

- Should this method prove effective in the mitigation of SPADs? **[Yes]**

- Can this model be considered as the ‘most appropriate’ within TFR railway operations? **[Yes]**