Extending a Distributed Cognition Framework: The Evolution and Social Organisation of Line Control

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Abstract

This paper continues the work started by Furniss (2004) and Furniss & Blandford (2006) to develop DiCoT, a codified method of analysis based on Distributed Cognition (DC). The existing method, developed through a practical application to the London Ambulance Service Central Ambulance Control Room, provides an analytic framework with which to understand the information flows and transformations in a system. DiCoT consists of three functional models aimed at structuring the analysis: Information Flow Model, Physical Model, and Artefact Model. This paper provides a test of DiCoT's existing framework in the analysis of a different domain, namely, line control at the London Underground Victoria Line control room. It provides reflections on the use of DiCoT in this context and suggests adaptations to the Artefact Model in order to examine in greater detail the interaction between practitioners and artefacts. Furthermore, the work here extends DiCoT with two new functional models based on DC theory and constructed to address the social organisation and evolution of practice. These models, the Development of Practitioners Model and the Development of Practice Model, are concerned with a DC perspective of how a system learns and propagates information over time. Such factors relating to the way in which the conduct of activity develops in the long term are deemed relevant to the major technological and organisational changes proposed as part of the Victoria Line upgrade. The application of the extended DiCoT framework helps to uncover significant differences between line control shift handovers and shift handovers in other domains. Finally, the scope of DC is critically examined in terms of its ability to act as the basis for extending DiCoT. The extended version of DiCoT provides a more complete DC framework with which to analyse team-based systems in terms of the social organisation and evolution of work.

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1 Introduction

The main aim of this report is to test the effectiveness of DiCoT, the codified method of Distributed Cognition (DC), extending and adapting the framework where necessary. In order to provide a suitable test context, DiCoT is used here as the framework for an ethnomethodological study of London Underground line control.

A secondary aim of the report is to contribute to the understanding of the domain of line control, in particular the issues surrounding the shift handover between practitioners, and to provide implications for change ahead of the London Underground Victoria Line upgrade. Since the main aim involves exploring areas where DiCoT could be extended, shift handover is a relevant focus of this study because it is an example of communication between practitioners where social factors not covered by DiCoT, including the organisation of work, are likely to be important. A brief review of research into shift handovers in other domains is given in section 1.2.

Line control is the manipulation of resources in order to maintain a safe and stable service according to a timetable. The activity involves collating information about the state of the line from multiple sources, interpreting this information and performing actions designed to minimise disruption and resolve incidents that threaten delays. This complex activity is time critical and involves the coordination of information between people and artefacts, and between people both internal and external to a control room.

DC is concerned primarily with the way an activity can ***emerge*** from the complexity of interactions between people and artefacts, and is therefore applicable to line control. As a theory, DC takes the view that cognition is not purely the product of internal reasoning but instead results from the engagement of representations both internal and external to the human mind. Crucially, as Hutchins (1995, pp 155) explains, interactions between the internal reasoning and the external tools do not merely amplify human ability, they ***change*** the problem so that human capabilities can be exploited to make the task easier.

Furniss & Blandford (2006) developed a structured method of DC to act as a bridge between theory and practice, and to aid analysts in applying DC to interaction-rich environments. This DiCoT framework was developed in the context of an ethnographic study of the London Ambulance Service (LAS) control room. The existing framework models concentrate on information flows, the physical layout of the environment and the nature of the artefacts used by practitioners. Furniss & Blandford (2006) identified areas pertinent to DC that were not covered by the original framework, such as the evolution of the practice and social factors. These areas are of likely relevance to shift handover and the organisational changes proposed as part of the Victoria Line upgrade, making this study a useful source of DiCoT adaptations.

Furniss (2004) gives a good introduction to the principles of DC and how they apply to the Information Flow, Physical and Artefact models of DiCoT. Rather than covering this ground again, the following section serves as a background and introduction to this study by examining the different approaches taken to studying Computer Supported Cooperative Work (CSCW) and where DC fits amongst them.

1.1 Studies of CSCW and the role of DC

A number of ethnographic studies have investigated how cooperative work supported by complex computer technology is carried out in a wide variety of domains. Studies of control room settings such as air traffic control (ATC), which have similarities to the domain of line control, have yielded rich insights into the way in which work is socially organised, for example, the work of the CSCW Research Centre at Lancaster University (Bentley et al. 1992; Bentley et al. 1995; Hughes, Randall & Shapiro, 1992) and Aarhus University (Mackay et al. 1998; Mackay, 1999). All these studies take a firmly sociological approach rather than structuring the ethnographic observation around explicit HCI theories, such as Distributed Cognition or Activity Theory. Instead, such studies are concerned with the situated nature of cooperative work and how this is the basis for important properties of these environments which must be taken into account in any redesign of relevant technology. For example, the CSCW group demonstrate that the reliability of ATC is based in the culture of cooperative cross-checking that controllers do through the use of flight strips, and that the redundancy and apparent inefficiency of flight strip use is what enables and drives controllers to perform essential cross-checking.[Ω]

DC is often regarded in studies that emerge from the discipline of social science as being either too constraining or lacking the analytical power to capture what is important. For example, Hughes, Randall & Shapiro (1992) deliberately distance themselves from referring to any theoretical orientation in order to let the work situation “speak for itself” without constraining the study to isolated aspects such as analysis of formal procedures or the use of tools. Bentley et al. (1995) are sceptical of the ability of DC to properly capture the elusive nature of practitioners’ skills in safety-critical domains. Interestingly, despite the stance taken to maintain distance from explicit HCI theory, the theoretical links do still exist in these studies. For example, in Hughes, Randall & Shapiro (1992) the adjustment of the alignment of flight strips in racks to highlight a problem can be traced to a principle of DC whereby people make use of the environment by creating “external scaffolding to simplify our cognitive tasks” (Furniss & Blandford, 2006; Hollan, Hutchins & Kirsch, 2000, pp 192).[Ω]

The seminal work of Heath & Luff in the context of London Underground line control is concerned with how collaborative work is socially organised, in particular how practitioners tacitly monitor each other’s activity and economically distribute information pertinent to line control (Heath & Luff, 1992; Heath & Luff, 1996; Luff & Heath, 2000). These studies draw on observations from a number of line control rooms and concentrate on the subtle communication that exists between practitioners as part of the work. For example, practitioners deliberately make their individual tasks

[Ω] These reflections originate from my OI(a) coursework on ATC visibly available to others who are not directly involved (Heath & Luff, 1992). Heath & Luff (1992) take a similar methodological stance to the CSCW group in claiming that DC "does not quite capture the situated and socially organised character of cooperative work."

In contrast to this approach, Fields et al. (1998) explicitly ground their analysis of ATC in DC theory on the basis that the external representations distributed throughout the artefacts and agents of the cognitive system are what matters in this highly information-intensive domain. The study's use of DC yields a deep understanding of the external representations of the domain because it allowed the researchers to attend exhaustively to a defined unit of analysis. In so doing, such a study is open to criticism because it does not yield some of the rich insights regarding the social nature of ATC. However, the focus provided by the theoretical framework of this study ***is its power***, especially since the framework is declared up front because it influences what is attended to during observation and it provides a clear link to any other studies that use it.[Ω]

Crucially, one of the strengths of DC is the nature of its scope, i.e. the breadth and depth of a domain that DC naturally enables the analyst to attend to. The unit of analysis is a functional system, i.e. one that is not constrained by physical boundaries, but that is defined by the functional nature of the activity in question. For example, this study is not limited to the study of a control room, although much of the relevant action takes place there; rather, it is the study of line control, which on occasion extends to technology and people beyond the control room. One of the advantages of viewing the unit of analysis in this way is that it invites systems thinking and therefore an analysis of ***multiple levels within a functional system***. DC therefore lends itself to two of the methodological considerations Nardi (1996) sees as important to an HCI framework, but which she only associates with Activity Theory, namely, "a research time frame long enough to understand users' objects [1]", and "attention to broad patterns of activity." Furthermore, Nardi (1996) seems to misconstrue the essence of DC focus by suggesting that the theory views people and things as conceptually equivalent: "We find in distributed cognition the somewhat illogical notion that artifacts are cognisizing entities." Hutchins (1995) does not claim that people and things are equivalent; rather, he claims that cognition can emerge from systems where sentient people and non-sentient things interact and he demonstrates that the cognitive properties of such systems are different to the cognitive properties of individuals. One reason why Hutchins' (1995) study is so rich with insights is that DC does not focus on providing a meaningless inventory of the properties of inanimate tools, but that it focuses on the complex interplay ***between*** people and tools.

Rogers & Ellis (1994) point out that a consequence of the fact that collaborative work is of interest to diverse disciplines such as cognitive, social and organisational psychologists, sociologists and anthropologists, is a plethora of different theories and frameworks designed to formally explicate work activities that frequently neglect to incorporate the research perspectives of each other's disciplines. Instead of viewing DC as a "lens" with which to focus exclusively on the tangible nature of external

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[Ω] These reflections originate from my OI(a) coursework on ATC

[1] "Objects" in Activity Theory refer to goals or motivations

representations, they claim that DC is a candidate framework for unifying technical, cognitive and social context perspectives. Referring to the work of Hutchins and his colleagues at the University of California (Flor & Hutchins, 1992; Halverson 1992; Hutchins & Klausen, 1992; Hutchins, 1995) and using examples of their own research, Rogers & Ellis (1994) argue that DC "can overcome the limitations of existing single-disciplined frameworks for studying collaborative working by traversing conventional disciplinary boundaries." They claim that when it comes to describing how new technology will impact on existing working practices, the traditional cognitive approach is to optimise independent displays for individual users, and the sociological approach is to preserve physical interactions because of their communicative social role. They argue that DC can play an integrating role because it instead aims to support the "interactive nature of information, as used cognitively and socially". By "interactive" they mean that DC interprets the external representations used in context as being coordinated with both the shared and individual knowledge of practitioners engaging in work activities. However, rather than attempting to promote DC as a radical direction for theoretical research, they recognise the framework's utility as a tool for understanding the complex nature of collaborative work in situ.

Ironically, it is perhaps the potential far-reaching scope of DC that lays it bare to criticism that its focus is too narrow because individual studies that draw on DC necessarily concentrate on one aspect of the theory. For example, Wright, Field & Harrison (2000) draw on DC to develop an approach to interaction modelling based on the concept of information resources. They concentrate on the coordination of external and internal representations that apply to interactions between one person and one artefact. They suggest that their Resources Model could be extended to a wider context but the strength of their work lies in demonstrating ***how cognition emerges from the interaction of internal and external resources*** and how this understanding can inform design.

The breadth of DC is demonstrated by Perry (1999), who identifies two distinct areas he terms as individually distributed cognition (IDC) and socially distributed cognition (SDC). IDC is concerned with systems consisting of a single actor and one or more artefacts, whereas SDC is concerned with multi-actor systems where physical artefacts either act as cognitive resources or as mediating structures for communication between actors. Perry points out the practical methodological and epistemological differences between the two areas, which suggest that compatibility between them in terms of research is problematic. For example, with its study of individuals and tools, IDC is seen as requiring a positivist approach, whereas SDC, where social coordination is the main focus, is seen as requiring an interpretive approach. However, Perry demonstrates that the two areas take a theoretically similar computational stance where the aim is to understand how cognition is manifested at a functional systems level. Furthermore, he argues that as long as we view DC as being an analytical tool that gives a (and not *the*) definitive description of a functional system, an analysis of a real-world setting can encompass IDC ***and*** SDC with a unifying language that applies to both these areas.

Hutchins (1995) comprehensively demonstrates that DC is capable of illuminating the rich and complex domain of ship navigation across all the concerns of IDC and SDC with this unifying language. The extent to which the unifying language and concepts of DC can be drawn upon for the adaptation and extension of DiCoT will be examined in the discussion of this report.

1.2 Studies of shift handover

Studies into the practice and function of shift handovers in nursing suggest that the handover involves complex nurse-to-nurse communication beyond the basic transfer of practical information (Lelean, 1973; Strange, 1996; Lally, 1999; Kerr, 2002). For example, Kerr (2002) views the handover as extending beyond the patient report, involving the management of informational, social and supportive functions, and that it should be seen as a valuable nursing asset. Lally (1999), in particular, views the handover as an important ritual, which “enables junior nurses to become competent members of the ward culture.” Strange (1996) highlights the subtle but important functions of handover in both promoting the shared vocabulary that underpins nursing culture and knowledge, and reinforcing the necessary hierarchy that characterises the profession. These studies suggest that the handover is instrumental in enabling nurses to ***understand what it is to be a nurse***.

A study of space shuttle mission controllers (Patterson & Woods, 2000) highlights the richness of information communicated during handover, and recommends that the automated logs designed to reduce the need for mission monitoring need greater sophistication if they are to be of use to human practitioners. For example, the information exchanged by controllers was at a much higher level, based on complex combinations of parameters, and rarely referred to the type of base data that automated logs typically deliver.

Both the informational complexity and the “hidden” functions of handover highlighted above warrant the use of a framework in this study that extends to examining social factors, and in particular how a line control system might learn and rely upon shared knowledge.

1.3 Structure of this study

Section 2 outlines the method used to gather, analyse and validate data.

The overall aims of sections 3, 4, 5 and 6 are to provide a high-level narrative of the study and to indicate how DiCoT was used to achieve the analysis. The full analysis is reproduced in the appendix.

Section 3 introduces the key findings of a DiCoT analysis conducted to understand the existing practice of line control for the Victoria Line at the Cobourg Street control room. The first part of section 3 (i.e. sections 3.2 and 3.3) describes the part of the analysis conducted using the original Information Flow and Physical models of the existing DiCoT framework. Section 3.4 describes the part of the analysis conducted using an adapted version of the Artefact Model. Section 3.5 describes the part of the analysis that relates to how the social organisation of the work setting contributes to how the system learns. Since this area lies outside the scope of the existing DiCoT framework, a new Development of Practitioners Model was built. Section 3.6

describes the part of the analysis that relates to how the practice of line control develops over the long term. Again, since this area lies outside the scope of the existing DiCoT framework, a new Development of Practice Model was built.

Section 4 describes the key implications for re-design arising from the analysis of line control.

Section 5 presents reflections formed regarding the use of the existing DiCoT framework. An explanation of how and why the Artefact Model was adapted is presented in section 5.4.

Section 6 explains how the new Development of Practitioners and Development of Practice models were constructed. It also shows how these new models relate to the existing DiCoT framework.

Section 7 presents the discussion and conclusion, in particular returning to the scope of DC and DiCoT.

2 Method

This section describes the method used to gather and analyse data for the study. The approach was exploratory in that, although some data-gathering was straightforward because it was directed by the existing DiCoT framework, extending this framework involved an iterative cycle of reviewing literature, gathering data and organising it according to new structures. For example, data considered relevant to DC concepts but potentially outside the scope of the existing DiCoT framework was gathered in order to retrospectively build extensions capable of describing the social and evolutionary aspects of the domain.

2.1 Data-gathering

The three-month study involved two separate data-gathering sources: observation and interview. The observation consisted of a series of five on-site observations at the London Underground Cobourg Street control room. The total observation time was 25.5 hours, with a session duration average of approximately 5 hours. The five observation sessions were conducted over a seven-day period and were planned to coincide with different shift handover times. The interview consisted of a one-hour session approximately a month after the observation sessions were conducted.

2.1.1 Observations

It was not possible to make audio or video recordings in the control room for privacy and union policy reasons and so the primary means of gathering data was extensive note taking. Photographs of artefacts and room layout were taken to both complement the notes and inform the design of diagrams, which are a major part of DiCoT.

The data collection method employed was Contextual Inquiry (Beyer & Holtzblatt, 1998), which combines observation of work in situ with informal interviews where the opportunity arises. This method was particularly effective for the domain of line control because much of the work can be characterised as long, quiet periods of monitoring followed by short, intense periods of action in response to an incident. Since it was clearly unacceptable to interrupt the practitioners during an incident, the stable aftermath of such an incident represented the ideal opportunity to clarify and expand the sketchy data gathered.

The existing DiCoT framework provided the focus of the observation sessions, i.e. the DC principles and type of data gathered by Furniss (2004) using Information Flow, Physical and Artefact models influenced those aspects of the line control domain that were attended to.

2.1.2 Interview

In order to gather data for the evolution of line control over time, some initial research was examined from sources of London Underground history but these proved incomplete with respect to the development of control room technology. In order to complete this part of the study, an interview was therefore conducted with two senior London Underground employees with extensive experience of various roles external and internal to the control room. The interview was semi-structured and based on pre-prepared questions informed by the initial research. The session was audio-recorded for subsequent transcription.

2.2 Data analysis

Notes were written up as soon after each observation session as possible in an unstructured manner. These notes were then used as the basis for a DiCoT analysis where data was structured according to existing Information Flow, Physical and Artefact models. Of the existing DiCoT models, only the Artefact Model was adapted (see section 5.4). The remaining data that related to social and evolutionary factors, together with the interview data, formed the basis for an analysis structured by the two new DiCoT models that were developed for this study: Development of Practitioners; and Development of Practice (see section 6). The structure of these models was derived from insights from Hutchins (1995).

2.3 Validation

The interview data was both supplemented with, and validated against, a number of historical sources relating to London Underground: Day (1969), Horne (2004) and Horne (2006).

The full DiCoT analysis, which appears in the appendix, was validated by one of the interview participants to ensure that data relating to London Underground and line control was factually correct.

In addition, a training CD related to one of the key artefacts, the Connect radio despatcher interface, was used to validate assertions made about its functionality. This was important because the claims regarding a lack of functionality made by one line controller could be checked, therefore allowing inference about why such a lack of system information existed.

3 DiCoT Analysis of Line Control: Key Findings

3.1 Overview

This section draws together the key findings of a DiCoT analysis conducted to understand the existing practice of line control for the Victoria Line at the Cobourg Street control room. The aim is to provide a high-level narrative of the analysis.

The first part of the analysis as presented here was conducted using the original Information Flow and Physical Models of the existing DiCoT framework, i.e. sections 3.2 and 3.3.

The analysis relating to key artefacts (i.e. section 3.4) was conducted using an adapted version of the Artefact Model. The adaptations and the need for them are explained in section 5.4.

The analysis relating to how the social organisation of the work setting contributes to how the system learns is presented in section 3.5. It was conducted using a new Development of Practitioners model, which extends the DiCoT framework.

The analysis relating to how the practice of line control develops over the long term is presented in section 3.6. It was conducted using a new Development of Practice model, which extends the DiCoT framework.

The full analysis is reproduced in the appendix.

The following table contains a glossary of roles and equipment referred to in this study:

Roles	
SC – Service Controller	Responsible for strategic decisions relating to maintaining a stable service.
SOI – Service Operator Information	Information assistant to SC.
SO – Service Operator	Responsible for implementing signalling operations.
TO – Train Operator (driver)	Operates train.
DMT – Duty Manager Trains	Manages Train Operator crews.
SM – Service Manager	Overall manager of line control.
Equipment	
FLD – Fixed Line Diagram	Large wall-mounted diagram showing track layout.
Connect radio despatcher	Connect is the network-wide radio system used by all lines on the Underground. The despatcher screen is what practitioners use to operate the radio.
Traction current control panel	Panel used to control the supply of

	traction current to the tracks.
Simlink	System used to inform controllers of the state of other lines. Information is controlled by the NOC – central Network Operations Centre.
Summary of Incidents	Spreadsheet used to record details about incidents.
TrackerNet	Online system that displays train position information on a track diagram.
Tunnel telephone	System used to communicate between SC and TO in an emergency.
Train listing screen	Shows train description and location information.
ATO – Automatic Train Operation	The technology that allows train speed to be regulated automatically without driver input.
Drico	A former type of driver-controller communication similar to tunnel telephone.
Carrier-wave	A former type of driver-controller communication that superseded Drico.
Identra	A system unique to the Victoria Line for entering train description information on a train.

3.2 Information flows (analysis conducted using existing DiCoT)

The aim of line control is simple: to keep the service running as closely as possible to the planned timetable and to do so with the minimum disruption. The means of achieving that aim however is highly complex and requires an efficient and well-drilled system of information flows that connect human practitioners sometimes via specialist equipment. The depth and variety of these individual communication channels are examined in greater detail in the appendix, but in order to introduce the activity of line control this section describes some of the key properties of the information flow system.

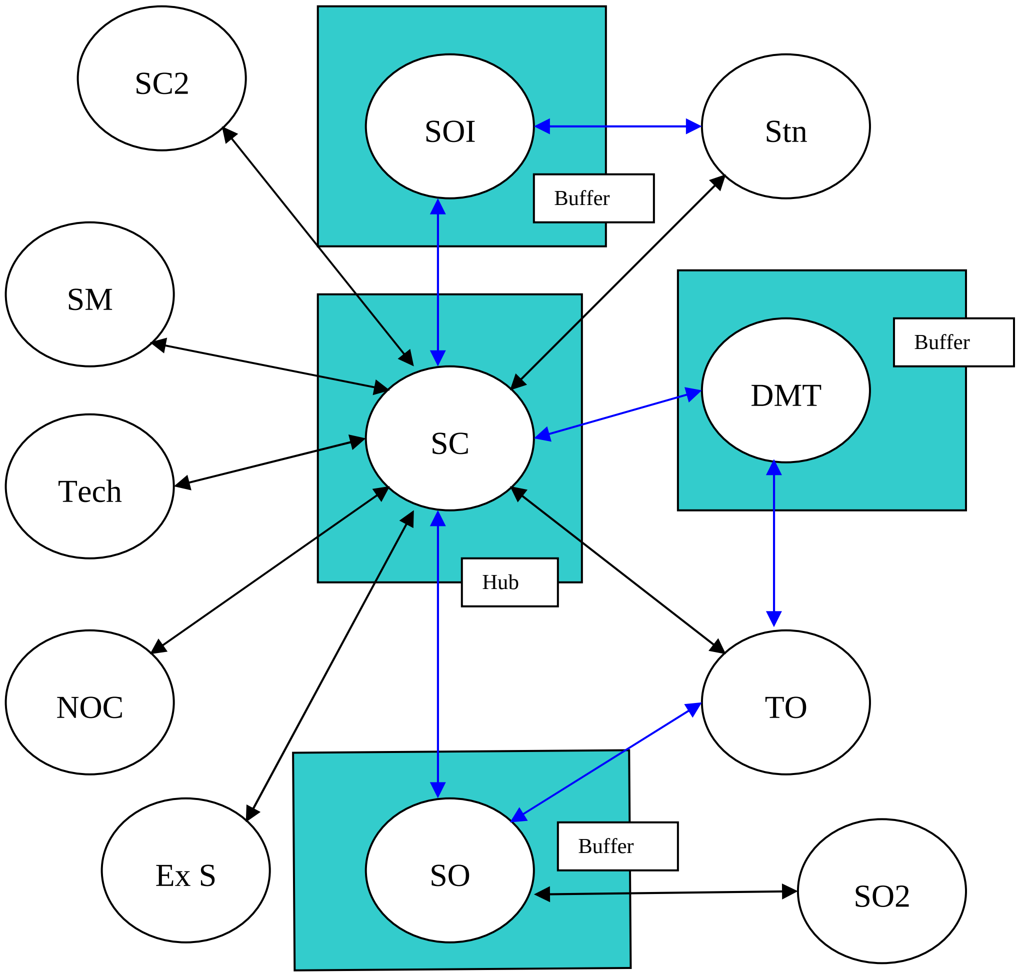
When the service is running smoothly according to timetable, the team of control room practitioners have little to do other than to maintain their awareness of the current situation in readiness for when an external incident with the potential to cause a delay occurs. When such an incident happens, the team must gather and interpret data from multiple sources, formulate a response and then act by changing the service in the appropriate way to bring it in line with the timetable, all the while checking the changing state of the system. The practitioners occupy different roles each designed to specialise in separate aspects of the practice of line control. They coordinate their activity in a highly integrated way, serving up and drawing the information they need from each other and from the wider system, acutely aware of the needs and expectations of their colleagues.

The diagram in figure 1 illustrates the practitioner roles, the communication channels between them, and the key properties of the information system. It is immediately obvious from the shape of the diagram that the key role is the Service Controller (SC) of which there is only one responsible for the line at any one time. As the main strategic decision maker, the SC can be regarded as a decision hub dealing with most of the flows of information entering the system regarding incidents, and subsequently orchestrating the responses aimed at resolving those incidents. The majority of these communications are verbal via telephone or radio but some of those that exist between the SC and the Train Operator (TO) are indirect, for example, the TO enters train ID information that is transmitted to the control room. Trains operate automatically on the Victoria Line through a series of codes transmitted via the tracks that determine the train's speed once moving. However since the train can be operated manually under certain circumstances and since the TO must initiate the train's movement, the TO can be regarded as influencing the train's position, information which is also transmitted to the control room. Information regarding train position and ID for multiple trains is collated and presented in several separate representations, which will be discussed in more detail below. For now, it is only important to understand that this information about the relative locations of all the trains in service is attended to independently by all control room roles and that it is compared with other external representations of information such as the current time and the timetable to determine the state of the line. Such a comparison may indicate that the service needs changing to synchronise it with the timetable. Alternatively, other verbal information regarding an incident that affects the service may be relayed from contacts external to the control room. Either way, it is the SC's responsibility to make a strategic decision to change the service to resolve the disparity with the timetable and such a "move" may involve cancelling a train, stopping a train to even out gaps in the service, reversing a train early, moving a train to temporary holding place at a platform or sidings, and reforming a train which involves changing the number/destination of a train.

Given that the SC acts as the central decision hub in the system and may have to coordinate communication with multiple contacts in rapid succession depending on the severity of the incident, there is a danger that he/she could become overwhelmed with incoming information. The SC therefore relies on other roles to act as buffers and filters of information. These important roles are the Service Operator Information (SOI) and the Service Operator (SO), both located in the control room, and the Duty Manager Trains (DMT) of which there are three for the Victoria Line; one mobile and two located externally at stations. The activity of these buffer/filters will now be examined in more detail.

The SOI filters information overheard from communications made by the SC (and others in the control room) and tailors it usually for the station staff who make announcements to inform passengers of the information they need to know about a particular incident. For example, for a faulty train that cannot proceed, this communication is typically delivered one at a time to a number of stations ahead of the train. Note that the SOI does not merely repeat information overheard from the SC, he/she transforms it into a *consequence*, i.e. how will this information affect the service from the passengers' point of view? The SOI therefore acts as a buffer by relieving the SC from having to transform and communicate incident information to stations. The SOI also pre-records messages which are retrievable via radio by station

Figure 1: Flow of information - key properties



Key

Letter	**Actor**	**Role**
SOI	Service Operator Information	Information assistant to service controller
Stn	Station staff	Supervision staff based at a station
SC	Service Controller	Responsible for strategic decisions to maintain service, and traction current.
SC2	2nd Service Controller	Acting as relief or assistance to 1^{st} SC
DMT	Duty Manager Trains	Manages train operator crews
SM	Service Manager	Overall manager of line control
Tech	Technicians	Diagnoses and repairs faults to trains
NOC	Network Operations Control	Central communications for all lines
Ex S	External services	Includes ERU (Emergency Response Unit) and BTP (British Transport Police). Also FRC (Fault Report Centre)
SO	Service Operator	Responsible for implementing signalling operations

SO2	2nd Service Operator	Acting as relief or assistance to 1st SO
TO	Train Operator	Operates train

staff answering passenger queries about the service. This activity acts as a buffer by encouraging station staff to consult these messages rather than contacting the control room directly.

The SO is responsible for implementing the service-altering "moves" the SC makes in terms of actual signalling operations. The SO's primary task is to monitor and record the service (by noting down the arrival and departure of trains at two specific locations on the line). SC and SO roles therefore remain in close communication regarding the movement and position of trains. Despite being positioned within earshot of each other, some safety-critical communication takes place via telephone and is recorded. The SO acts as a filter/buffer by converting SC instructions about moves into signal operations, thereby relieving the SC of the need to do so. The SO also acts as a buffer between SC and TOs by relieving the SC of the task of making the minor corrections to the service that entail contacting TOs and instructing them to hold at stations. SOs are also responsible for authorising safety-critical moves, such as passing a signal at danger which is known to have failed. Only the SO can authorise these moves because the SO is regarded as the ultimate authority on train location. The delegation/implementation relationship between SC and SO is not clear-cut and depending on their relative experience, the SO may act as a decision-support to the SC suggesting the strategic moves that will synchronise the service with the timetable. Finally, since the SO is primarily engaged in monitoring the state of the line, the SC relies on the SO to act as an early-warning system to spot potential delays and problems.

The service-altering "moves" the SC can make obviously affect the TO. If for example a train is to be reformed, it will then enter a new pattern on the timetable perhaps requiring it to remain in service for longer than it was originally planned to be, therefore conflicting with the shift needs of the TO. For this reason, moves are planned to coincide with a change of TO (either because he/she is due a break or the shift is over). The DMT manages TO crews and will be consulted to ensure that there is a TO available to pick up a newly reformed train and to relay instructions to the TO, perhaps to change the train ID accordingly. The DMT therefore acts as a buffer between SC and TOs by providing a single point of contact regarding crew availability, relieving the SC from having to make repeated communications directly with crews. Since the DMT is better placed to keep abreast of changes out in the field (such as lateness, sickness, mistakes etc), he may also act as a decision support by suggesting options open to the SC through a process of negotiation.

As the main decision hub of the system, the SC is involved in the majority of communications that take place with external contacts, either via telephone to fixed locations such as the station supervisor's office, or via Connect radio to a mobile handset. Most of the telephone communication takes place via a touchscreen telephone, although there is also a manual back-up telephone and a dedicated tunnel telephone for communicating with TOs during safety-critical incidents. The touchscreen telephone makes communication simpler by representing pre-programmed contacts as aliases and is used for those contacts who either do not have access to the Connect radio system (such as Network Operations Control (NOC) or British Transport Police (BTP)) or for those contacts who otherwise cannot be contacted via radio for some reason. The majority of external communications with other London Underground staff is however conducted via Connect radio, which will be discussed at greater length in section 3.4.

The remainder of this section will examine the communication that occurs between SCs, in particular during shift handover.

In general, the handover process is informal and rapid (often no more than 2-3 minutes) especially if the line is quiet. The process can be split into three phases: preparation phase, handover phase, and completion phase.

Preparation phase: In the hour prior to shift handover, SC1 (the outgoing SC) writes entries onto a separate page of a logbook (ordinarily used to record SC decisions). The entries contain all those outstanding out-of-the-ordinary pieces of information that SC2 (the incoming SC) will need to know in order to control the line, i.e. those pieces of information that would prevent or hinder SC2 in the activity of line control if they were not made known. The entries are deliberately short (often in abbreviated form or shorthand) and they contain only as much detail as is absolutely necessary. This type of communication requires a shared understanding as to what terms mean and what their implications are. The entries tend to be relevant for an entire shift, such as any faulty equipment the SC routinely uses, rather than detailing transient problems. A faulty train for example is not mentioned in the handover documentation but may be referred to verbally.

Handover phase: The handover phase begins as SC2 enters the control room where he/she will immediately pick up cues as to the state of the line. Gaps on the large Fixed Line Diagram (FLD) that indicates the position of trains will indicate a problem with the service. The noise and atmosphere of the room is another cue – relaxed banter and laughter indicate periods when the service is running normally according to timetable, whereas during an incident the room will be noisy but business-like. During non-busy periods, both SCs run through the handover sheet entry by entry, sometimes referring back earlier in the logbook or referring to the FLD. During an incident however, SC1 will be too busy to run through the handover sheet. SC2 has to build up an awareness of the situation from observing SC1 and listening to his/her communications. Much of the operational verbal communication inside the room and over the phone/radio is repeated: either requesting clarification or confirmation, so SC2 will tend to pick up the gist of problems quickly and may use the back-up touchscreen telephone or spare training handset for the Connect radio in order to listen in to communications. As a matter of course, SCs tend to deliberately “tidy up” sub-problems in an incident so that they have one less thing to deal with. This practice helps to simplify the handover and gives SC2 a clear point in the sequence of activity to start taking over. SC1 may give short summaries/updates on unfolding problems at opportune moments between calls.

Completion phase: At some point, SC2 will feel confident enough to take calls. SC1 will continue assisting until it is clear SC2 has the situation under control. Unless it is very busy, this is usually signalled when SC2 takes a call or takes control of the timetable of which there is only one on the desk. SC1 will support SC2 past the end of his/her own shift if required although SC1 will rely on SC2 to be skilled enough to take over quickly. When the line is busy, the written handover sheet may not be used at all but it is there as a reference should SC2 need it later.

The handover process detailed here provides an opportunity to examine the complexities of the SC role because the interaction between SC1 and SC2 ***is necessarily made explicit***. Of course, from a distributed cognition perspective, one SC working alone must expose much of his/her reasoning because of the communications that must be made, but the handover during an incident makes the complexities ever more apparent. With its informal and rapid nature, the handover process is deceptively simple but it is effective and generally seamless. During an incident, a successful handover is achieved by both SCs integrating their activity with an emphasis on the following:

- A concentration on the salient information (i.e. no extraneous details)
- A shared understanding of how problems develop and should be solved
- Trust in each other's abilities
- A clear understanding of the boundaries of responsibility

The boundary of responsibility is a particularly important property of the system because only one SC has responsibility for the Victoria Line at any one time. In other words, SC1 and SC2 both know this and negotiate in a largely tacit way to ensure that "ownership" of the line is transferred unambiguously and totally. This is one reason why the handover is usually so brief. The relationship between SCs, and in particular the boundary of responsibility, is highly relevant to the organisational changes proposed as part of the Victoria Line upgrade and will be discussed in greater depth in section 3.5.

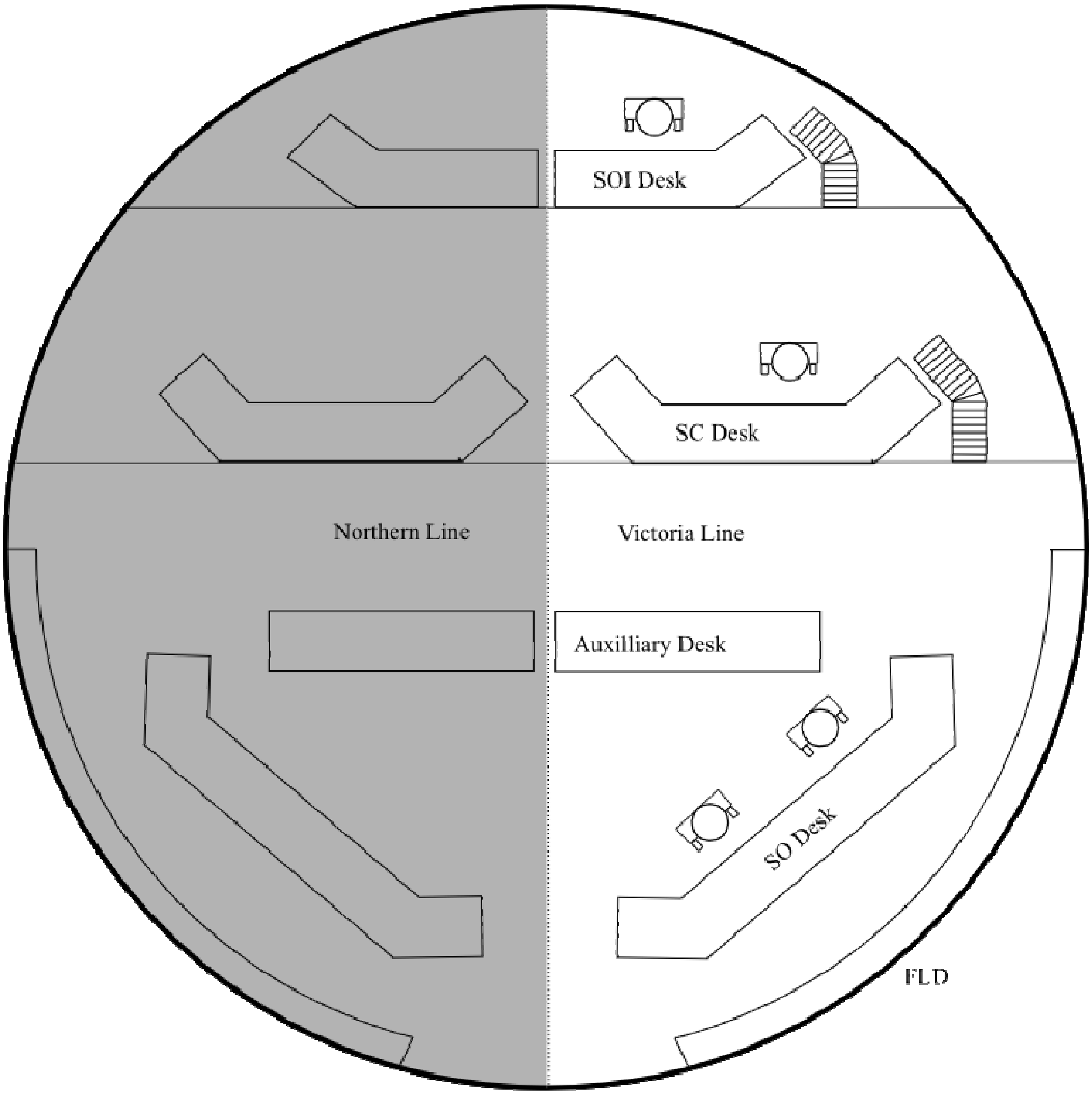
3.3 Physical layout (analysis conducted using existing DiCoT)

The physical layout of the system in terms of the spatial relationships between artefacts and people has important properties that influence the information flows discussed in the previous section. At a high level, the layout of the Cobourg Street control room "fits" the requirements of the different practitioner roles in terms of the proximity and access to equipment and each other. This current layout has to some extent evolved to accommodate the changing demands of line control, as will be demonstrated in section 3.6, a fact that indicates the importance of the influence the physical arrangement of the system has over performance.

The control room accommodates both Northern Line and Victoria Line control although they are operated independently of one another. However, some benefits regarding the way the system "learns" accrue from this physical arrangement and these will be examined in the section 3.6. There are three desks for each line, for SOI, SC and SO roles, with each desk on a different tier, the SOI desk being on the highest tier and the SO desk being on the lowest tier. All desks face the relevant FLD. The position of the SC desk on the middle tier reflects the role's nature as a decision hub. The close and direct nature of the communication channel between SC and SO is reflected in the SC's clear view of what SOs are doing and the way the SO desk is angled so that face-to-face contact is easily maintained. The SOI needs to overhear and see the SC but face-to-face communication is not a priority, and the SOI's elevated position behind the SC reflects this. The relative distance between SOI and SO reflects the lack of a required information flow between them and may serve to inhibit unnecessary communication. The proximity between all three roles allows them all to hear each other normally and promotes shared awareness, strengthening the ability of the system to monitor events and transfer knowledge efficiently. All three roles have an uninterrupted view of the FLD, although the best view is reserved for the SOs, reflecting their priority to monitor the state of the line. Despite its overall size, much of the labelled detail on the FLD (e.g. station names and signal numbers) is small and not easily readable even by SOs. However, this does not cause a problem because practitioners know where the stations are from memory and by the shape of the diagram. Even the poor light in the room, which affects the legibility of the FLD text, helps to highlight the illuminated strips that indicate where trains are on the tracks. It is the relatively distant positions of the SOI and SC from the FLD that affords these roles ***the view they require***, i.e. the relative positions of trains and the gaps between them.

The SC desk (see figure 3) can be regarded as an information hub where the SC receives visual information from stations via CCTV; information from external sources via telephone and Connect radio; information about the location of trains via the radio despatcher screen, train listing and TrackerNet screens; and information about the state of other lines via the Simlink screen. This information must be integrated and coordinated with other train location information provided by the FLD and in particular with the timetable in order for the SC to make the strategic decisions necessary to line control. The central position of the communications equipment affords easy access and reflects the SC role as a communication hub. The traction current control panel is rarely used and has a peripheral position to avoid accidental activation. Also, the fact that there is only one and it is positioned to one side of the desk reflects its safety-critical function and that only one SC should be responsible for it at any one time. Similarly to avoid confusion, there is only one timetable, one logbook and one copy of the traction current and signal diagrams book. Timetable and logbook are always kept centrally on the desk in front of the screens.

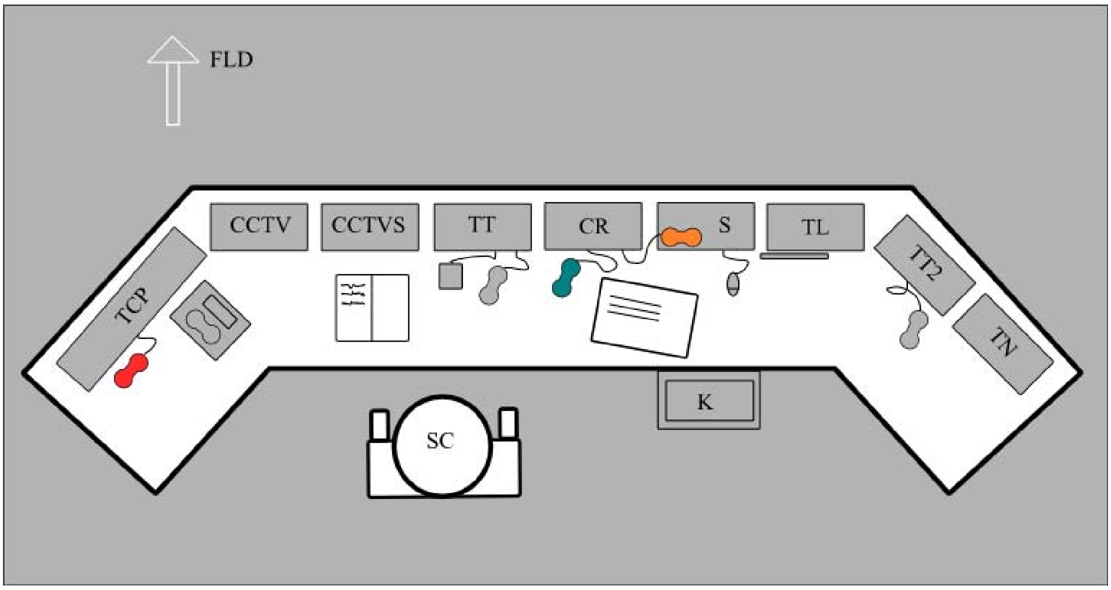
Figure 2: Control room layout



When the service is running smoothly according to timetable, one SO working alone can monitor and record it. However, two SOs are always on duty and will share the work if the service is busy (see figure 4). The task is physically partitioned and the SO desk and equipment is ***arranged to best support two SOs***; one responsible for the north end and one for the south end of the line. The equipment they need is duplicated and is configured to be relevant to either north or south end. In the case of the control panels, which control the programme machines that operate the signals, this configuration is physical. The Connect radios can only make and receive calls for north or south areas of jurisdiction. The paper record sheets are relevant to either Seven Sisters (north end) or Victoria (south end). The fact that the north/south partitioning of the desk is obviously orientated to give appropriate views of the relevant halves of the FLD only reinforces the permanent and inflexible nature of the arrangement, i.e. when one SO is responsible for the line, he/she has no choice but to split the task up according to a north/south partition. In the current arrangement, this is not necessarily a problem especially given that the task of monitoring a smoothly running line is simple for an experienced SO. However, it will become clear later in the document that the partitioning of the line along physical criteria whether fixed or dynamic is an important issue for the proposed upgrade.

Some of the key equipment referred to in this section will now be examined in more detail.

Figure 3: Layout of SC Desk



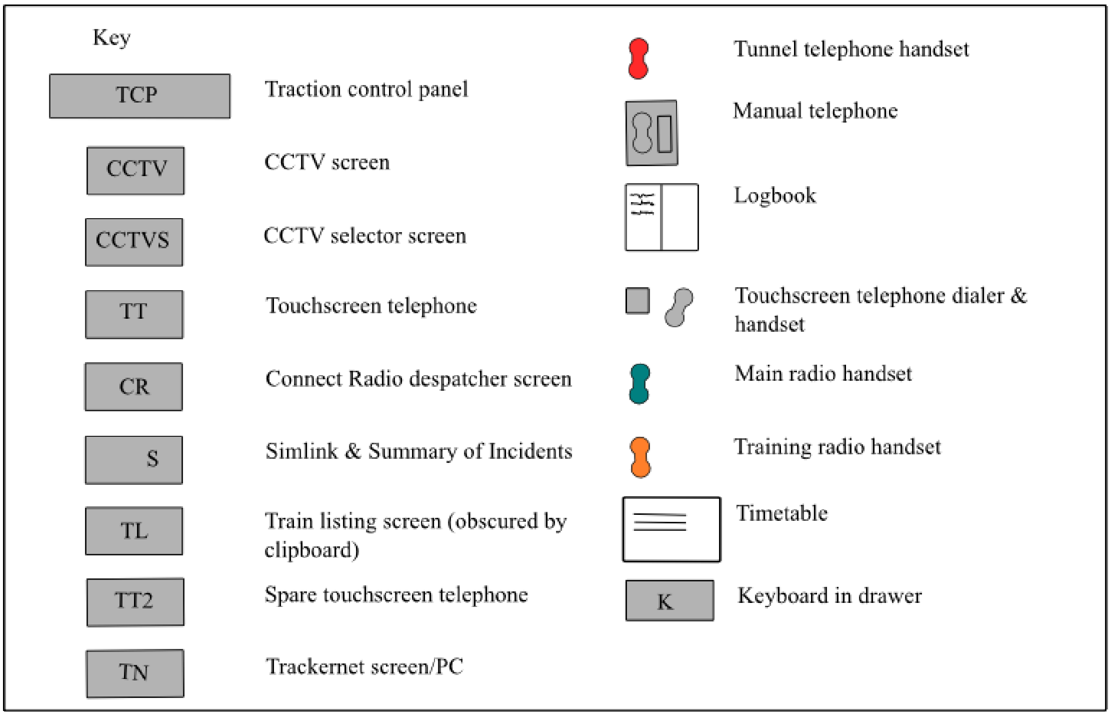
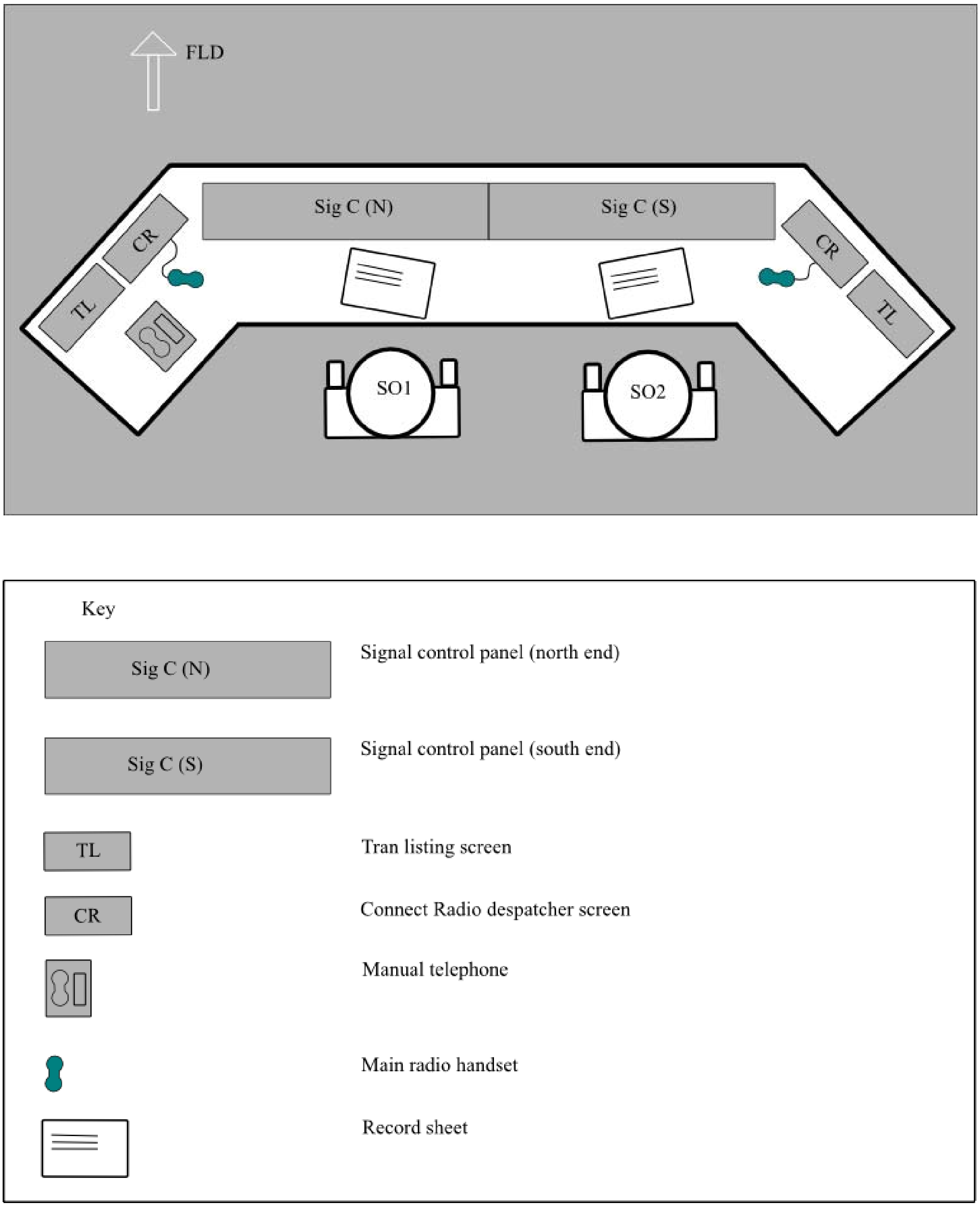


Figure 4: SO Desk layout



3.4 Key artefacts (analysis conducted using adapted DiCoT)

SCs often mention that there are three things that remain essential for line control: the FLD; the Connect radio; and the timetable. The design of these artefacts, in particular the external representations of information embodied by them, has a profound influence on team and individual cognition and therefore on the performance of the system as a whole. One of the interesting aspects of these key artefacts (and indeed most of the artefacts in the control room) is that they are shared. This is most apparent with the FLD since there is only one for the Victoria Line, although it is also true that the radio is shared in that the ***same key information*** presented by different despatcher screens is available to all practitioners. Similarly, there are several copies of the timetable that contain the same basic information despite the fact that they may be tailored for different roles (for example, the SO record sheets are cut-down versions of the full timetable designed to facilitate the recording of train movements). The attempt to tailor localised views of the radio despatcher screen and timetable according to the needs of the roles suggests that if it were required and feasible, the same would be attempted for the FLD. The fact that varying quality of access to the detail of the FLD as imposed by the position of the roles does not appear to cause the system problems also suggests that although the roles share the FLD, they use it in different ways. This claim will now be examined.

The appendix contains a full analysis of key artefacts and goes into some detail to incorporate the Resources Model (Wright et al., 2000). The full analysis describes how the line control artefacts inherently embody external representations of certain types of abstract information structures, such as plans, goals, possibilities (or affordances), history, action-effect relations and states. According to the model, information can only be a resource for action if it has a representation, one that is either external (i.e. as realised in an artefact's design), or internal (i.e. in the user's mind), or distributed both internally and externally. The conduct of an activity such as line control results from the coordination of these external and internal resources by practitioners. For example, suppose that in response to an incident the SC decides that northbound trains are to be turned early onto the southbound track at Seven Sisters. In order to implement this, the SO will identify the relevant section of the track by its shape and its horizontal position on the FLD rather than by labels. The localised portion of the diagram with its associated programme machines, track configuration and signals constitutes a set of structural possibilities or affordances. A stream of lights representing northbound trains arriving at this part of the diagram constitutes a list of goals (i.e. the set of trains that must be re-routed). This list of goals, although ordered, is not a plan because it does not contain the actions necessary for trains to be re-routed. Rather the plan, i.e. the sequence of actions that must be performed to achieve the goals, is not external but internal. The SO must formulate a plan based on what must be done and what is possible but this plan has no external representation in the artefacts at his/her disposal.

Furthermore, as all practitioners are acutely aware, the lights on the FLD do not necessarily represent trains, just the presence of an object on the track. They are skilled at interpreting what the patterns of light changing over time on the FLD truly represent. For example, a series of uninterrupted lights may represent a set of bunched up static trains (and therefore a potential delay) or it may represent a physical problem with that section of track. This level of uncertainty is further captured by the fact that none of the lights are associated with representations of a train's number or destination. This means that the SO must coordinate this FLD representation of train location with other external representations such as those provided by the timetable, the train listing screens, the Connect radio despatcher screen, and the verbal confirmations of other staff (including potentially the TO) to arrive at a conclusion about *which* trains the lights represent. This conclusion is stored internally. The SO keeps her place in the plan by recording a history of train movements in the record sheets. Action-effect relations (i.e. causal relations between actions and system states) exist in manuals and rule books but in practice they have become entirely internalised as SO knowledge. The SO's control panel actions re-route the trains and consequently change the state of the FLD and other artefacts. During this activity, the SO can be regarded as adopting a ***plan-following strategy***, i.e. coordinating a pre-formulated plan with a history of goals. By contrast, the SC, who has access to the same FLD as well as other external representations, can be regarded as adopting a ***plan-construction strategy***, i.e. reducing the difference between current state and goal state by selecting from possibilities to formulate an altered plan, where the goal is defined as "normal service". The different interaction strategy adopted by the SC reflects his/her role in making strategic decisions, in this case the decision to reverse the trains early as a response to some perceived problem with the service as a whole, a problem that is not of any immediate relevance to the SO. This analysis therefore indicates that the same FLD is indeed used in different ways at least by SO and SC roles.

SCs generally regard the Connect radio as the most useful tool for communication because it can be used to contact people on the move and people whose location is uncertain. Connect is a highly flexible radio system capable of facilitating simultaneous communication between different groups of handset holders and allowing handset numbers to be associated with meaningful aliases. However, during observation its full capabilities were not utilised. For example, technicians (in contrast to station staff – see below) are personally assigned radios, therefore the numbers could be associated with their names/roles, but SCs manually dial the numbers which are written in biro on the screen surround as a reminder. Indeed one SC who harboured a keen understanding of what flexibility was possible complained that the system did not offer such capabilities. There are several possible explanations for this state of affairs:

- Firstly, the SC may not be aware of the full functionality of the system, i.e. it is a problem of training.

- Secondly, the system is not capable of meeting what the SC wants or needs, i.e. the functionality Connect offers is known by the SC but this functionality is not exactly what the SC requires, so he/she persists with the inefficient but easily remembered ways of contacting people. In other words, he/she lives with it.

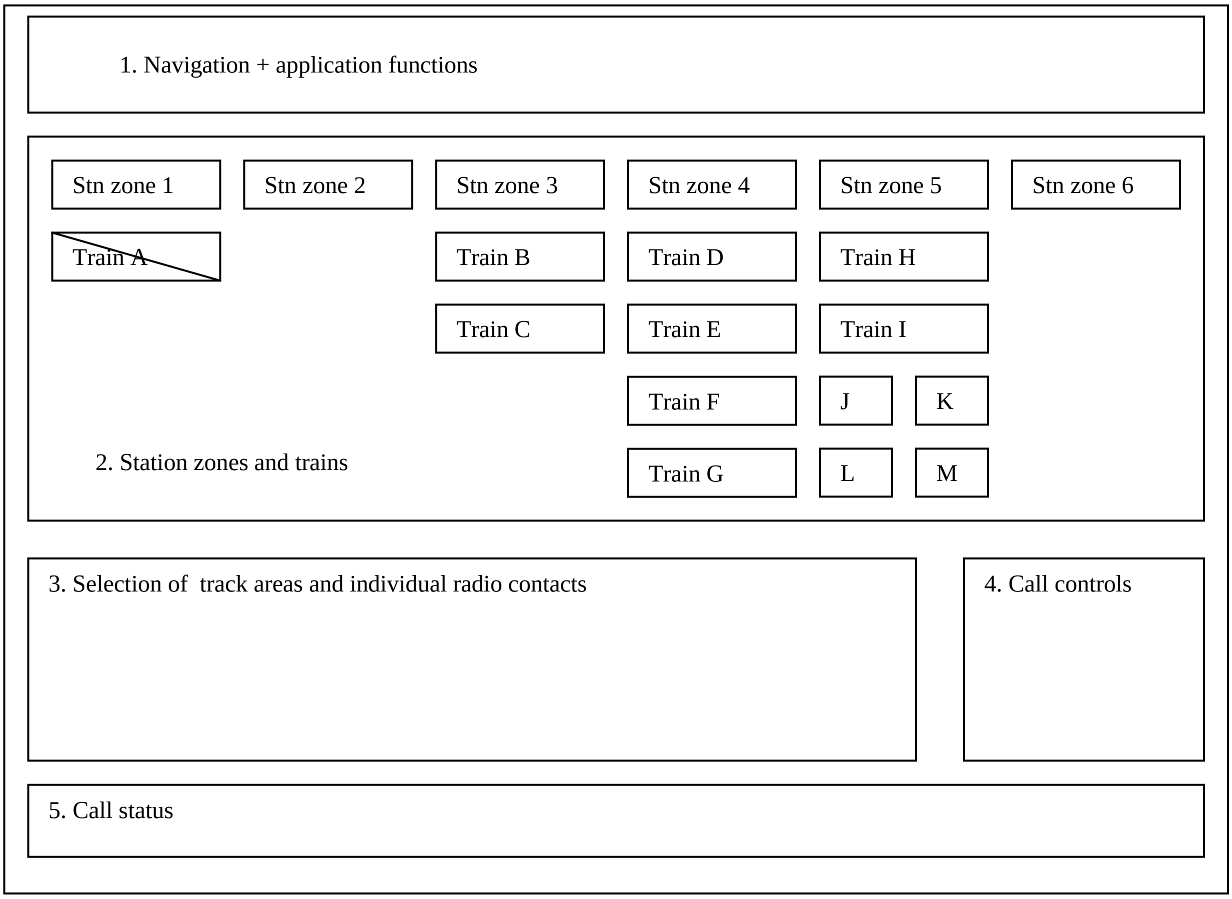
- Thirdly, the system provides the required functionality but the configuration of the equipment makes it difficult or impossible to utilise that functionality. For example, the radio can be used to make group calls or 1-to-1 calls. However, radios in stations are not personally assigned to individual members of staff – rather each person picks up an available handset from a pool. It would therefore be useful for the SC to make a group call to a station, rather than to a particular handset, because a group call will be attended to by any station staff holding a handset. However, the Connect radio's functionality is tied to user-groups, and group calls to stations are disabled for the SC user-group. The SC therefore resorts to 1-to-1 access, dialling 5-digit numbers that correspond to radios held at a particular station. A physical directory of these numbers is permanently kept on a shelf on the SC's desk, however looking up the

> numbers is time-consuming and inefficient because the SC may try several numbers until she finds one that answers. Interestingly, the SC can log out of the despatcher screen and log in as a member of the SOI user-group to gain access to the station talk-groups but in practice this is not done. This may be because the SOI user-group cannot make 1-to-1 calls to individual trains, functionality which is vital to the SC. Another reason is inconvenience, i.e. the ability to access station talk-groups represents a benefit that is outweighed by the cost of the interactions involved. This behaviour is further reinforced by the fact that SCs (as well as other practitioners) prefer to keep the despatcher switched to a particular screen known as the mimic screen and are reluctant to switch out of it without good reason. The mimic screen is popular because it gives a further indication of the location of trains. However, it is interesting to note that the mimic screen was not designed with this use in mind; rather, SCs learned to use it in this way. The layout of the screen is described in more detail below.

Figure 5 shows the approximate layout of the mimic screen. The central part displays up to six station zones at a time arranged as columns, labelled with abbreviations denoting particular stations. The station zones are ordered geographically north to south from left to right, following the convention of the FLD. These labels are disabled functions for an SC user, enabled functions for an SOI user. Within each column is a list of trains currently located in that zone. There is no direct representation of which direction the trains are travelling (northbound or southbound). Train movements can be tracked by watching train representations disappear from one station zone and appear in an adjacent zone, and from this a train's direction can be inferred. Each train representation is also a button that enables contact to be made with the TO.

Applying the Resources Model (Wright et al., 2000), in response to an incident, the SC may make a plan internally about which contacts to call and in which order. This plan is not represented externally by the system. Similarly, the goal, "all relevant contacts called in line with resolution of an incident" is not externally represented. A guideline of who to call and in what order according to the type of the incident is taught to the SC who subsequently internalises it and may modify it "on the fly" depending on the unfolding specifics of the problem. The mimic screen does however represent a number of communication possibilities: trains and stations that are located in the affected area. The stations are not directly contactable from the SC's mimic screen but the representation does still show them and the rough geographical relationships between them. One of the reasons the mimic screen is kept as a preferred default is because it presents these possibilities. Combining communications, for example, to a station, technician and driver can be achieved by setting up a patch but only by switching to a different screen and therefore temporarily losing sight of the mimic screen with its representation of train position. The history of which communications have been made (and therefore where the SC is in the plan) is externally recorded in the logbook. A history of call-back requests can be saved via the radio and this can help the SC to make further calls to the same contact without the need to remember or look up the number again, but this external representation suffers from a number of problems: it needs to be actively maintained on a different screen; the history does not record anything about the content of the call (whereas the logbook can); the history does not distinguish between separate incidents, i.e. calls are recorded in the order they are made and received, whereas the logbook can separate sets of calls if required. Interaction strategy can be described as a combination of plan following (i.e. of an initial pre-formulated plan) and plan construction “on the fly”.

Figure 5: Connect radio despatcher – Mimic screen



In general, the representation of train location provided by the mimic screen is coordinated with other external representations such as the FLD, timetable and train listings screens in order to increase the SC’s confidence about where trains are. What is interesting is that there is no one perfect source of this information that SCs rely on – rather they attempt to reduce the uncertainty associated with a single source by combining separate sources.

The timetable provides the SC with a number of different functions: it helps in the location of trains; it is marked up by SCs to show the opportunities for changing the service; it can be annotated to record history; and it assists in determining the overall state of the line. The information the timetable contains is replicated in the information loaded into the programme machines that control the signals.

The timetable page is essentially a grid with individual trains represented as columns, the stations on their routes as rows, with times of departure (and occasionally platform number) shown in the intersection cells. The column headings show train information: running train number; trip number; and crew number. Stations are always organised so that trains move “down the page” regardless of direction, i.e. a southbound train will start at Walthamstow at the top of the page and move to Brixton at the bottom of the page, then when it becomes a northbound train, a new page will depict the journey from Brixton (top of the page) to Walthamstow (bottom of the page). Note also that time increases both vertically and horizontally in the grid and that diagonals (in the bottom left to top right direction) roughly show constant time. SCs are highly practised at exploiting the timetable structure to find information. For example, if the service appears to be running normally (i.e. to timetable), the presence of a train at a station on the FLD will be combined with the time as given by the 24-hour clock on the FLD. Time and station will be coordinated with the timetable to find a train number. Thus the SC will be reasonably confident of the ID of the train represented on the FLD (and by implication the IDs of the trains immediately south and north of this train). By following the diagonals of constant time, an SC can see where all the trains on the line are meant to be at any point in time.

Figure 6: Timetable page

Page details; day, direction (i.e. northbound, southbound)

	Trn 1	Trn 2	Trn 3	Trn 4	Trn 5	Trn 6	Trn 7
Station 1		y	z				
Station 2	y	z					
Station 3…	z						

The timetable pages are covered with transparent plastic to allow the SC to annotate the information with an erasable chinagraph pencil. Vertical lines through columns indicate, for example, that a train is cancelled. Arrows denote a different order of trains and vertical lines with a horizontal base indicate that the train is to be sent to the depot. These marks coordinated with timetable information function as an external history – helping the SC to keep track of changes.

More permanent annotations are made to the actual timetable pages to highlight opportunities for SC service moves which assist in planning. Specifically, red rings are drawn around trains where the TO is due to change (because of a shift end or break). These are seen as opportunities to reform the service because a change to the number of the train has implications for the existing TO's shift and so using these "pick-up" trains simplifies matters. A detailed example of how the timetable assists in reforming the service is given in the appendix, section 9.3.3.

Applying the Resources Model (Wright et al., 2000), in response to an incident, the SC uses the timetable as an externalised goal (i.e. a representation of the ideal service). The red ring annotations are possibilities. The annotations to the plastic covers and logbook entries serve as an external history of moves, and as an externalisation of action-effect relations (i.e. changing a train number may set off a chain reaction whereby other trains in service must have their numbers altered until all the duplicates are resolved). The individual steps and branches of the plan are still internal to the SC. The interaction strategy is one of plan-following.

This treatment of the key artefacts has concentrated on how the practitioners, in particular the SC, interact with external representations in order to conduct line control. This description paves the way to study how that interaction between people and artefacts might change if the system is altered (see section 4.3 for a description of the implications for the re-design of key artefacts).

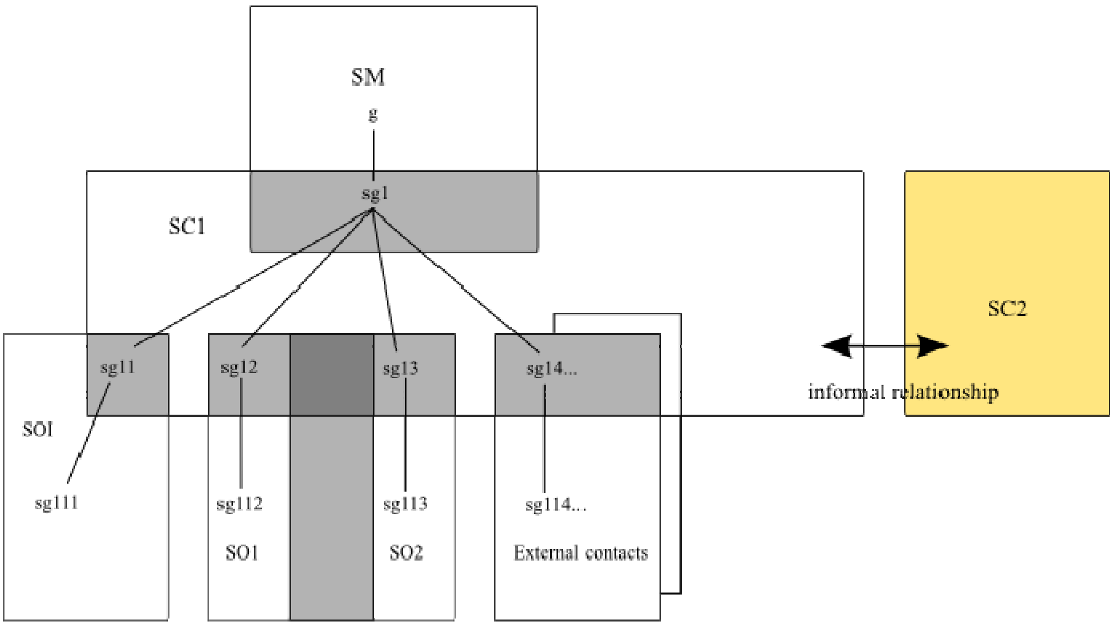
The analysis so far has dealt with the practice of line control as it currently stands. However, an examination of how the practice has come to be the way it is enriches the understanding of it and provides insights into what it might become. Referring to Simon's (1981) parable of ant movements on a beach, Hutchins (1995) points out that the progression of ant behaviour from random searching to focused targeting of a food source tells us more about the changing landscape with its legacy of chemical trails than any intelligence of the ants. In the same way, the current generation of line control practitioners have adopted the artefacts, strategies and lessons developed and left behind by previous generations. It is this evolution of both practitioners and practice that will be examined in the next two sections.

3.5 Development of practitioners (analysis conducted using new DiCoT model)

The development of practitioners here is concerned with how the system learns through the developing knowledge of the control room staff. This knowledge is accumulated over the span of practitioners' careers and is strongly influenced by the way work is socially organised, i.e. through the relationships between roles in the system. Another determining factor of the knowledge that accumulates in the system is the previous experience of control room staff, and this is shaped by the recruitment policy of the organisation.

Figure 7 depicts a snapshot view of the way the current activity of Victoria Line control is socially organised in terms of the relationships that exist between key practitioners. It shows the hierarchy of roles, their overlapping goals and areas of responsibility. For example, the SM's overall goal (g) may be broken down into a number of sub-goals, one of which (sg1) forms the primary goal of the SC1 under his command. Sub-goal sg1 is the shared responsibility of both the SM and SC1. Note how the sub-goals that contribute to the overall goal can be met independently between levels (e.g. sg111 is accomplished independently of the SM and outside his immediate area of responsibility). These shared goals and lines of command form the basis of the social relationships between roles. The diagram is complicated by the presence of SC2, a controller for the Northern Line. SC1 and SC2 do not explicitly share responsibility or goals although an important informal relationship exists between them, one that is explained in detail below. SC2's relationships are similar to those of SC1 but are not shown for reasons of simplicity. It is important to note that there is a separate SM for the Northern Line.

Figure 7: Social organisation of line control (adapted from Hutchins (1995) pp 203))



What is important here is the way in which the practitioners relate to each other rather than the information flows between them. Hutchins (1995) describes the way in which a hierarchical structure can map to a goal structure such that areas of assigned responsibility overlap between superordinate and subordinate ensuring that sub-goals of the overall goal are satisfied. This organisational structure not only influences the way in which work and responsibility is shared but shapes the way knowledge is learned and retained in the system.

In line control a hierarchical structure exists although, at least within the control room, the nature of it is less rigid and clearly defined than in the military setting Hutchins describes. The SOI and SOs instead actively support the SC rather than receiving orders. In particular, the SOs may offer advice and negotiate with the SC to arrive at a solution.

Before the 1990s all promotion by grade within London Underground was conducted on the basis of seniority. Competence was checked through exam performance but the key to promotion opportunities was length of service. In terms of line control, only the SC role has traditionally remained outside this regime. This recruitment policy ensured that career progression was slow but it also resulted in the build-up of a pool of knowledge for practitioners to draw upon during the activity of line control.

A good example of the system of seniority applies to the SO's role described by one SO as "dead man's shoes" in that a candidate would have to wait for positions to become free following death or retirement. Originally known as signal controllers these practitioners had to come from a signalman background. Typically they served an apprenticeship in a signal cabin starting from the age of 15. By 20 they might make signalman, cabin man at 25, then relief signalman who could operate different signal cabins. The role of SO differs from a remotely based signalman in many respects, for example the increased complexity and responsibility that comes from operating the entire line with a manager overseeing performance. However, the years of knowledge gained from working at remote signal cabins are valuable to the SOs in understanding how the technology works out in the field. Once an individual becomes an SO, he/she tends to remain in this role because of a lack of pay incentive to change roles (see below).

By contrast, SCs (originally known as line controllers) could be recruited from anywhere, although they were often recruited from within the system, for example ex-TOs. Since the role of TO has changed considerably with the evolution of technology ensuring that this task is largely automated, the TO is seen as less of a proactive problem-solving role than it once was, especially since the advent of radio that allows TOs to be more reliant on the SC. More recently, a lack of suitable candidates for the role from within London Underground resulted in SCs being recruited from military or police backgrounds since it is thought that these candidates possess the structured thinking and effective decision-making skills necessary for dealing with incidents, especially safety-critical ones.

Generally, previous experience from within London Underground is highly valued, for example, SOIs are often ex-TOs. Some SCs have extensive experience of many roles: SO, station supervisor, TO etc. It is unlikely however that once practitioners have reached the control room that they will change roles due to a lack of incentive. This is because the pay structure of SC, SO and SOI roles do not vary considerably. This is in contrast to the military setting described by Hutchins (1995) where knowledge is accumulated through career progression: as each successive position is learned, the knowledge gained is useful to the next position.

A detailed examination of the most important individual relationships is supplied in the appendix, but what follows now are just the key findings from this examination that are relevant to the upgrade.

The inevitable mismatch of goals that arises between two practitioners may result in tension. For example, the SM who has ultimate responsibility for operational decisions and for the smooth running of the service with the minimum of delays, has a high-level goal of keeping track of and reducing delays from the overall perspective of running cost. The SC, on the other hand, is concerned with making safe operational decisions that result in as few delays as possible, but is not directly concerned with the financial cost of disruptions. The mismatch of goals here may result in tension between the two, however the tension rarely causes a problem because of the mutual respect that arises from the fact that the SM may have experience of service control and because the boundaries of each other's responsibility are clearly understood by both parties.

In order to compensate for the relative lack of career movement within the control room, knowledge is actively shared (both formally and informally) so that each role understands the expected responsibility and tasks of other roles. In practice the boundaries of responsibility may be blurred when the knowledge is transferred. For example, although the SC retains overall responsibility for the strategic decisions relating to line control, depending on the relative experience between SC and SO, the SO will suggest moves that alter the service as well as merely implementing them. People are in general acutely aware of others' backgrounds and so they know who to ask or rely on if the activity requires knowledge outside of their personal expertise. The importance of this type of knowledge transfer can be inferred from the introduction and subsequent removal of a glass partition positioned between SCs and SOs. The partition was aimed at reducing "unnecessary" communication and forced the use of the recorded phone link between SC and SO. The design was found to be unworkable in practice, because it complicated communication during incidents, interfered with the close social relationship between SC and SO, and inhibited the negotiation of line control work so vital to the transfer of knowledge.

Although the relationships within the control room are not overtly hierarchical (except perhaps during a busy incident), the hierarchical relationship between the SC and external contacts is explicit (with the exception of SC-DMT – see appendix section 9.4). One senior SC was observed to reprimand a trainee about the manner of her communications over the radio to a TO: "You don't ask them if it's all right to do something. You're the controller – you tell them what to do." This style of verbal communications is about engendering the right tone crucial to safety-critical situations rather than pulling rank. The precise language and careful protocols that the SC must adopt for safety-critical situations both defines, and is fundamental to, the relationships between the SC and all external contacts, and is described in detail in the appendix, section 9.4.

Practitioners are trained to be able to perform their roles on both the Victoria Line and the Northern Line. Control of the lines is entirely separate but SCs frequently cover for each other during comfort breaks and may sometimes assist each other when one line is busy and the other quiet. Their behaviour on these occasions provides not only insights into the relationship they have with each other but also into the implicit boundary or horizon of responsibility they operate within. One Northern Line SC covering for his Victoria Line colleague answered an external call but would not make a decision: “I know what I’d do if it was me, but it’s not my railway.” Technically, the SM has ultimate operational responsibility for the line but this is usually delegated to the SC without interference, so that the SC responsible for a particular line can be regarded as the ***only authority*** on that line (except for authorising TOs to pass signals at danger which is the responsibility of SOs). This means that other SCs (even those with more experience) will not encroach on that boundary of responsibility. They will only take a message and pass the relevant information on, perhaps offering advice if asked for it. Trainees and inexperienced SCs come to this understanding by watching how other SCs relate to each other. The function of the behaviour has its origins in the safety-critical attitude required by the work and in the efficiency that results from having just one SC in charge of a line, but it also reinforces the respect that SCs have for each other.

After a period of classroom instruction, control room practitioners learn “on-the-job” under the supervision of a senior practitioner. A trainee SC may know the procedures for a particular type of incident but will learn what it is to be an SC from watching other SCs in action. This is evident in the following example. The general atmosphere in the control room is lively when the lines are quietly operating to timetable. The banter and horseplay is tolerated, even encouraged, partly to guard against boredom and partly to build team spirit and morale. Despite appearing not to be maintaining awareness of the state of the line all experienced staff are in fact acutely tuned to the cues that indicate that work is necessary. There seems to be a pride in this behaviour of participating in banter but being able to respond instantly to incidents if required, and it may have a purpose in practising the kind of multi-tasking that is useful in the job. One trainee SC who had been in the control room only a week was swapping jokes comfortably with Northern Line staff but then was suddenly faced with several incidents at once. Others carried on joking around her (without including her) but she hesitated. The trainer instead of asking for hush admonished her: “Keep your eye on the job. You’ve got a radio call waiting…”

The social relationships that have been described arise from the organisational structure that develops to share the responsibilities and workload of line control. The organisational structure is intimately linked with the way the practice of line control has developed over decades in response to technological change. This relationship between organisational structure and technological change will be examined in the next section.

3.6 Development of practice (analysis conducted using new DiCoT model)

This section concentrates on drawing out the major trends from the period of approximately 50 years spanning the late-stage planning of the Victoria Line in the early 1960s, the official opening in 1968 and the 40 years of operation until 2008 just prior to the proposed Victoria Line upgrade in 2012. The legacy of technology that was in existence prior to the opening in 1968 is considered in terms of its direct effect on the technology that was chosen to implement the Victoria Line. The organisational structure, i.e. the way in which the line was staffed, has its origins in high-level operational decisions on matters of cost and efficiency. Major technological change and organisational change have occurred at the same time and closely influence one another. External events, in particular the King's Cross disaster of 1987, also influenced technological change and therefore the practice of the line control conducted using that technology.

Figure 8 illustrates the 50-year period of the planning and operation of the Victoria Line in terms of a number of significant timelines. Note that the period depicted in the diagram starts 8 years prior to the opening of the Victoria Line, which was brand new in 1968, i.e. it was not an adaptation or extension of an existing line. Each timeline relates to a different set of evolutionary developments, either organisational or technological. For example, timeline 3 relates to technology for communicating between driver and control room staff. The circles represent points of major change where one development is superseded by another. For example in timeline 3, the Drico system paved the way for, but was replaced by, Carrier-wave technology. Each timeline is covered in more detail in the appendix, section 9.5. The arrows in Figure 8 indicate the important dependencies that exist between the organisational structures and technologies shown on timelines. For example, train listing technology depends upon Identra train description technology. Note that the horizontal positions of the arrows have no relation to actual points in history.

It is sometimes not possible to identify the exact nature of the causal forces at work for the development of a practice such as line control. An attempt has been made in Figure 8 to indicate the direction of such dependencies but this is an interpretation only, based on the understanding of those London Underground employees interviewed. For example, one view is that one-man trains **necessitated and therefore drove the introduction of** more comprehensive and reliable communication links with the control room. Another view is that improved communications technology merely added weight to the decision to introduce one-man trains. What remains clear, however, is that the organisational change and the technological change occurred at the same time and that a dependency exists. In reality the dependency is probably bidirectional. This assertion can be related to Carroll's Task-Artifact Cycle (1990), which describes how a task implicitly sets requirements for the development of artefacts designed to achieve that task, but that the use of an artefact often redefines the task for which that artefact was developed. In other words, the development of tasks and artefacts are closely coupled, in the same way that technological and organisational change are coupled.

Organisational and technological change on the Underground has historically been slow and incremental mainly for reasons of cost and safety. The fact that different lines operate and can develop independently of each other has encouraged this incremental nature. This can be seen in the way communications have developed. Prior to the Victoria Line opening in 1968, the Drico system for enabling communication between driver and controller that was grafted onto the tunnel telephone system still suffered from limitations such as: the train had to be stationary; the train had to be in a tunnel; and the driver had to initiate the call. Radio technology was unworkable in the 1960s because signals were absorbed by the tunnel walls, so a system known as Carrier Wave was developed that relied on speech signals being sent through the conductor rails. Despite its limitations, Carrier Wave improved upon the sporadic nature of Drico and proved the case for improved continuous communication, paving the way for experimental development in radio technology. Each significant improvement in radio technology justified the introduction of a newer radio system to the line that was undergoing upgrade work at the time. The rapid pace of change in this communication technology compared to the pace of planned upgrades could actually be exploited so that isolated lines could be the test-beds for change prior to a more extensive roll-out. Despite the innovations offered by newer radio systems, Carrier Wave persisted on the Victoria Line, which was the last line in the early 1990s to upgrade to radio communication. This was because the system, although not perfect, worked, and the cost of a radio replacement was not justifiable. The downside to this incremental evolution was the proliferation of disparate systems and lack of standardisation across the Underground as a whole, a situation that was eventually tackled with the introduction of the network-wide radio system, Connect.

Figure 8: Development of practice (see next page)

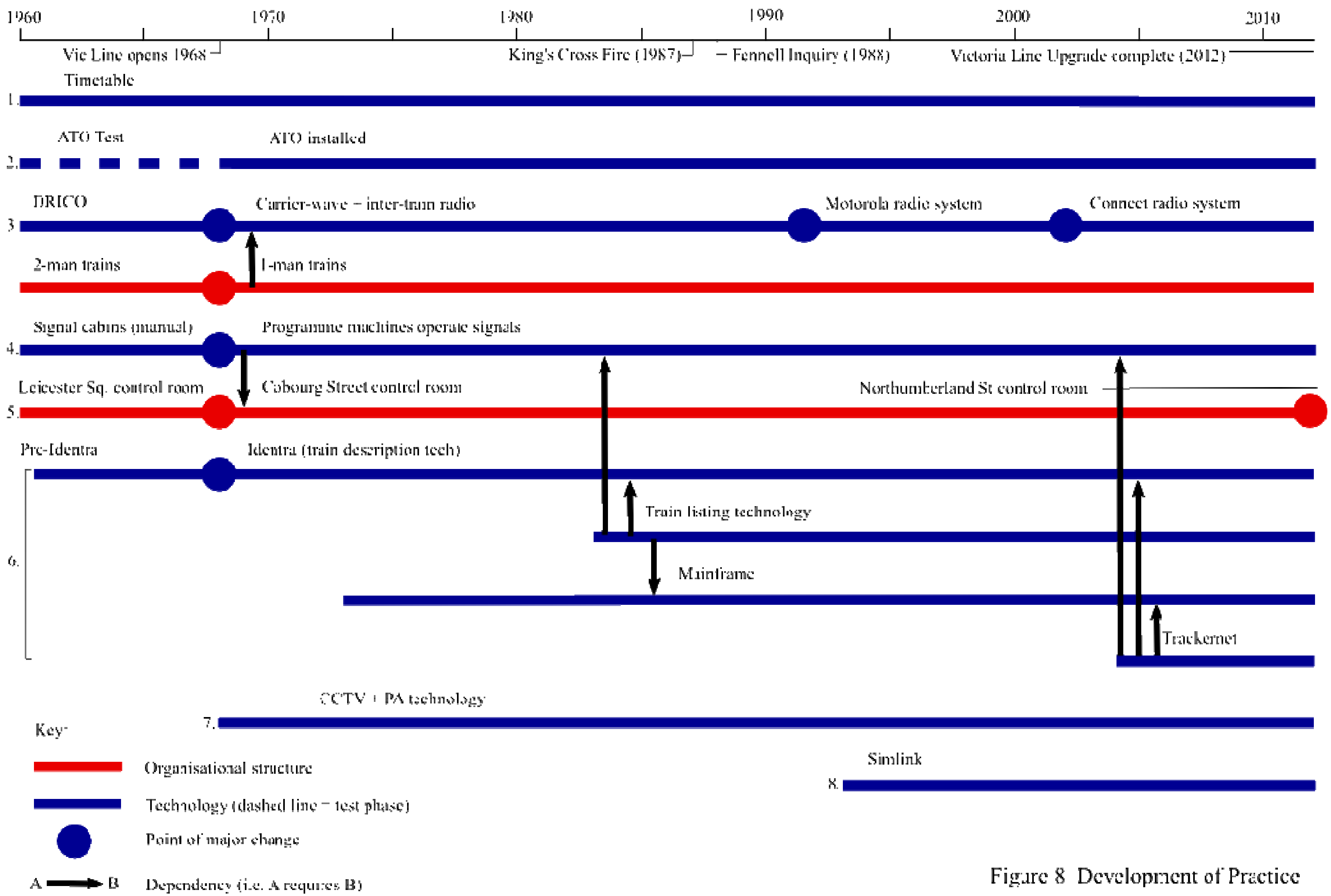


Figure 8 Development of Practice

Further evidence of the slow incremental nature of change on the Underground can be seen in the way existing technology, such as the train-listing screens, is left in place to back-up or complement newer technology, such as the Connect radio screens. One major reason existing technology is left in place is because it is rare that the newer technology fully supersedes it in terms of functionality. For example, the Connect radio mimic screen shows information about train location and is useful because this information is integrated with the means of contacting TOs on those trains. The train listings screens, however, show a calculation of the number of minutes a train is delayed by, information not displayed on Connect. Furthermore, the sources that provide the information regarding train position are different for the two technologies, thereby furnishing the system with redundancy and the ability to compare discrepancies, factors that are essential in increasing the confidence practitioners build up about where trains are. Interestingly, TrackerNet relies on the same sources of information that supply the train listings screens, but again train listings screens show different information, a fact that ensures their survival. Furthermore, despite the fact that TrackerNet combines train position information with a diagrammatic representation of the line, this technology is barely used by Victoria Line practitioners mainly because it is prone to failure and that failure is often not apparent unless practitioners notice that the information ceases to refresh.

The slow pace of change is most evident in the evolution of control room structure. The newly opened Victoria Line had a dedicated control room at Cobourg Street, which followed approximately the same organisational structure as it does now with a controller (SC), two signal regulators (SOs) and one Line Information Assistant or LIA (SOI). The relatively slow evolution of technology in the control room is partly attributable to the persistence of this organisational structure.

The general trend away from a distributed and towards a centralised system of control can be identified from the wider changes instigated by the opening of the Victoria Line in 1968. The replacement of remote signal cabins and staff by programme machines that operate signals automatically, the improved communications between TO and control room, and the introduction of technology such as CCTV drew control and responsibility into one central location.

At a different level there is a simultaneous counter-trend towards distributed rather than centralised control in terms of the control of individual lines. The move from the original Leicester Square control room (that served all lines) towards individual control rooms (each serving usually one line) has continued since the Cobourg Street control room was introduced. This organisational change reflects the understanding that different lines should be operated separately. The resultant downside of such a distribution of control is a loss of inter-line communication, a situation that had catastrophic consequences during the King's Cross disaster. In order to compensate for this, following recommendations made during the Fennell Inquiry, critical information about other lines is now fed into the Network Operations Centre (NOC) and propagated via Simlink to all line controllers. This is another example of how organisational changes (i.e. the NOC) and technological changes (i.e. Simlink) are closely coupled.

Perhaps the most obvious trend that emerges from the diagram in Figure 8 is that since its inception in 1968 the use of technological support relevant to line control has increased dramatically. Furthermore, the proliferation of technology is accompanied, and perhaps partially explained by, the fact that technological innovations persist in parallel with each other rather than being superseded. The timelines labelled 6-8 illustrate this trend, clearly showing that individual technologies such as train listings and TrackerNet are evolving separately and are not characterised by major points of change.

Taken against the sedate evolution of the Victoria Line control room over forty years, the relocation, change of equipment and organisational structure of the proposed upgrade represents the most significant single change in its history. It is in the context of this change that the implications for re-design will now be examined.

4 Implications for re-design

The Victoria Line upgrade, due to be completed in 2012, consists of new signalling equipment (aimed at improving journey time capability), new rolling stock, a new control room and new control room equipment. It is also proposed that the current control room roles, SC and SO, will be merged to form one new SC "Level 2" role with responsibility for some strategic decision-making and the implementation of moves designed to maintain a stable service according to timetable. As part of this organisational change it is envisaged that the SM will take on some extra responsibility for strategic decisions. The new rolling stock and track technology will enable a more frequent service capable of satisfying increased passenger demand. As a consequence of this it is envisaged that the SC Level 2 role will be more demanding during incidents, and therefore under these circumstances responsibility for controlling the line will be shared with each practitioner being assigned a separate physical section. Depending on the situation, two SCs will divide the line into a maximum of seven areas of control, negotiating between them which areas to take responsibility for. For example, one might take control of the single area affected by an incident, with the other taking control of the other six areas thereby managing the rest of the service around the incident. Thus the boundaries of responsibility will shift dynamically between them in line with what is happening on the line. These proposed changes have profound implications for the way in which line control is conducted and therefore fundamentally affect the re-design of control room layout and equipment. Implications are grouped according to the same topic headings used to discuss the key findings: information flows; physical layout; key artefacts; development of practitioners; and development of practice.

4.1 Information flows

The prospect of two Level 2 SCs taking responsibility for different sections of the line opens up a debate on what partitioning of the communication system will prove to be most effective. For example, group calls via Connect radio to only those TOs on a particular section of track is a possibility. One existing SC claimed that such a facility would not be useful because of the uncertainty surrounding train location information, i.e. such a group call may erroneously include or exclude TOs that are on the boundary of a zone arbitrarily defined by the system. Improved accuracy and reliability of train location information (see Section 4.3 on key artefacts below) would not necessarily solve this. The issue is more about the arbitarily drawn boundaries of responsibility and the fact that trains are moving. Supposing SC1 is responsible for the section north of King's Cross and SC2 is responsible for the section south of King's Cross. SC2 wants to make a group call to trains in his section. A southbound train that has not quite reached King's Cross yet will not receive the call. It might enter SC2's zone of jurisdiction after the call and therefore the TO will be unaware of the delivered information. Furthermore, it may be difficult for the SC to know which trains have picked up the message or not. An analogous situation with zones of the same line being the responsibility of different controllers currently exists at the Baker Street control room, which covers the Circle Line. The Circle Line is largely a logical construct with trains physically running on track “belonging to” the Metropolitan Line and the District Line. The control centres for these separately run lines are located in the same building but different rooms. A Circle Line train may, for example, leave the Metropolitan Line controller’s zone of control and enter the District Line controller’s zone of control. If the Metropolitan Line controller (MSC) is making a group call while the train crosses into District Line jurisdiction, then the train “drags” that call into the new zone until the call has finished. Similarly if a train crosses from District Line jurisdiction to Metropolitan Line jurisdiction while MSC is still making that call, then the train will not receive the remainder of that call. Controllers at Baker Street do not tend to be concerned about this situation. This is because they operate with the assumption that the intended recipients of a group call have received the communication, although they are aware that this is not guaranteed because the TO may have turned down the volume of the handset. Currently, on the Victoria Line with one SC responsible for the whole line, the Connect boundary issue is not a problem. Typically, SCs word their messages to TOs in such a way as to define groups of recipients, e.g. “Message for all drivers on the southbound approach to Highbury…” More important than exactly where a train is located is **where a train is heading**, something that the current Connect technology is not equipped to distinguish. A train in SC2’s area travelling northbound and about to leave the area at King’s Cross will receive a message that may have little relevance to the TO at that moment. Interestingly, a drive towards more targeted communications may not necessarily result in improvements. The Motorola radio system that was superseded by Connect was not enabled to make 1-to-1 calls, only group calls. This limitation shapes the way SCs design and word their messages, but it also means that all TOs receive messages whether they are intended recipients or not, thereby helping TOs to build up an awareness of what is happening elsewhere. Some TOs complained that the advent of 1-to-1 calls reduced this awareness.

The proposed merging of SC and SO roles effectively closes the issue surrounding phone communication between the two roles, in particular the uncertain circumstances under which the phone should be used. The system gains in simplicity from the removal of one channel of communication but it potentially loses a record of the distributed decision-making that accompanies changes to the service. This lost verbal communication will therefore be unavailable to the SOI to act upon. Perhaps more importantly, however, the system loses the explicit on-the-job transfer of knowledge that results from SC-SO communication. It remains to be seen whether this loss will be compensated by a different type of SC-SC communication, especially as the new zones of jurisdiction will be controlled separately.

An insight into the type of communication that might exist between two SCs responsible for adjacent areas of the line is provided by the shift handover. The handover process can be regarded as a negotiation surrounding the transfer of responsibility, a situation that may be important in the new organisational structure where the boundaries of responsibility are dynamic, for example where a faulty train remains in service but moves from one area of jurisdiction to another. Key findings related to shift handover suggest that its apparent simple informality is a product of a close integration between SCs. This integration relies on trust, a shared understanding in how problems develop and should be solved, and a shared understanding in the boundaries of responsibility that exist between them. One of the reasons the current shift handover process is so seamlessly successful is that only one SC is meant to be responsible for the line at any one time, so transfer of “ownership” is unambiguous. Localised jurisdictions that expand or shrink in line with a developing incident, and moving trains, are likely to complicate the boundaries of responsibility and entail more complex communication.

This claim is further backed up by the nature of the communication that currently exists between two SOs responsible for north and south ends of the line. During an incident, SOs communicate closely with each other about the location of trains, checking and double-checking with each other and their equipment to increase their confidence in the information. The success of this communication is partly due to the fact that their areas of jurisdiction are ***fixed***.

Shift handovers are complicated by uncertainty. This is evident during an incident where the longer, more involved handover that takes place between SCs relates to their role, one that demands practitioners to react to unfolding and uncertain situations. It is also evident in the more straightforward handovers that occur between SOs even during an incident where the monitoring nature of the job itself simplifies matters. This suggests that the proposed merging of SC and SO roles will require a shift handover that is at least as complicated as the one that exists between SCs, possibly more complicated given the complexity introduced by shifting boundaries of responsibility. The handovers between SCs and SOs in the existing organisational structure are smooth and simple but the challenge for the upgraded system is to preserve this situation. The introduction, for example, of system logins may disrupt handover efficiency and distract practitioners from the real work of line control.

In the proposed upgrade structure, the loss of the SC-SO communication channel is counterbalanced by the gain of a new Level 2 SC-SC communication channel. The role of SC as decision-hub may be enhanced by the prospect of two Level 2 SCs discussing the optimum solution to a complex incident. It is possible that the new communication required here will be more involved because of the greater variety of choices posed by the collaboration, the greater scale and frequency of incidents implied by the technology enhancements of the upgrade, and simply because of the greater need for verbal updates between the two practitioners. There may therefore be a more urgent need to improve the decision-making capability of the hub. For example, giving inexperienced SCs access to intelligent, searchable electronic versions of paper documents, such as the Defective In Service Instructions (DISI) that provides advice about whether a faulty train necessitates being taken out of service for repair or not, may speed decision-making and accelerate learning. (See section 4.3 for more examples on how further coordinating the external representations that relate to train location may improve SC performance).

The move to two Level 2 SCs raises some further questions regarding the role of SC as communication hub, for example, how will external contacts be routed to the appropriate Level 2 SC? Those communications that are by nature tied to a physical section of the line can simply be routed to the appropriate Level 2 SC, e.g. station staff for particular stations. However this leaves those external contacts that are not so easily associated with a physical section of the line. For example, the locally based DMTs will negotiate with the SC responsible for the relevant section of line. However, it may be that information arrived at through these conversations must be propagated when the SC boundaries of responsibility change dynamically. Decisions about reforms to the service affect the whole line, so SCs may negotiate a sharing of the work such that only one of them will handle reforms. Since the train crew relief point is based at Seven Sisters on the north section of the line, this is likely to be the north-end SC. However, an additional train crew depot is planned for Brixton on the south section, so this may change.

The fact that there is just one traction current control panel reflects its safety-critical status. The presence of two Level 2 SCs, who may be dealing with separate incidents that require decisions about traction current, necessitates a system of control that is safe, visible and accountable, e.g. who has access and under what circumstances?

Changing the organisational structure will affect other information flow properties of the system such as buffers. For example, currently in the role of buffer/filter the SOI attends to one SC. The proposed upgrade structure allows two Level 2 SCs to work in parallel to resolve potentially more than one incident at a time, making the SOI's task of overhearing relevant information more difficult. The loss of SO as filter, buffer, decision-support and early-warning system has further implications for the Level 2 SC role. In particular, a Level 2 SC must give more attention to the monitoring of the line currently performed by the SO. This may cause conflicts of priority if the Level 2 SC is to remain a decision-hub fielding information from multiple sources. The signal operation implementation of strategic moves will therefore need to be simple, demanding the lowest possible cognitive workload to achieve.

4.2 Physical layout

At the level of control room, the reduced number of practitioners implied by the proposed organisational structure of the upgrade suggests a simplified but largely unchanged layout. The room layout partly depends on whether there will be a shared equivalent of the FLD. Level 2 SCs will need greater access to the type of information currently supplied by the FLD but it may be replicated locally and electronically for each practitioner. One of the benefits of this arrangement is that each practitioner will potentially have access ***to more detailed clues about what other practitioners are attending to***. The importance of such access is evident in observations of the current layout when, before attempting to use the PA system, the SOI checked to see whether the SC was already using it.

At the desk level, the key to the design is how to physically support the partitioning of the line into up to seven different areas of control. Clearly, to avoid an inefficient proliferation of equipment required by replicating the equipment for each physical area (in the way desks and equipment are arranged for the north/south partitioning of the line for SOs), the solution entails providing duplicate sets of equipment for the two Level 2 SCs and giving them the means to flexibly configure their equipment to the desired areas of control. This solution also allows one Level 2 SC to operate the line efficiently.

4.3 Key artefacts

The lack of perfect reliability and accuracy of information regarding train location is not necessarily a problem to existing practitioners. As has been described, practitioners are highly skilled at picking up the information they need from separate displays to build an awareness of where trains are. They know how much weight to give to a piece of information and when to ask for confirmation from TOs and each other. They exploit the separate and redundant nature of the different train location sources in order to spot discrepancies. Of course, improving the quality of this information will aid SC decision-making and is important because the complexity of line control will increase as a result of the upgrade. The Northern Line (a more complex line) currently employs the use of Positive Train Identification (PTI) where train IDs are transmitted to the control room and displayed on the Northern Line FLD. However, even PTI is not 100% reliable due to signal interference and Northern Line SOs make use of a dedicated CCTV screen simultaneously showing images from four cameras positioned to provide a visual check of the train ID shown on the front and reverse train cars. PTI will be available for Victoria Line upgrade trains (09 stock) although accuracy still relies on the TO entering the correct train ID information. As long as train location information remains less than 100% accurate and reliable, it is crucial to allow SCs to continue to build up their awareness of train location via access to multiple and separate sources of information. The designer could aid them in this task by ***facilitating coordination*** of those separate sources of information. The following suggestions are to be viewed as examples of how coordination of different external representations might be achieved:

- Once a train is identified, its ID/number could be “tagged” on its moving representation on the FLD to show which train practitioners in the control room think it is. This would save practitioners from having to mentally “tag” the train, which currently involves remembering the ID/number and following the progress of FLD lights. Tagging trains with staff expectations of ID may however lead to a dangerous reliance on the reliability of that information.

- Alternatively the Connect radio mimic screen information could be combined with the FLD information regarding train position and track layout to make comparisons between the two easier. The timetable information is already combined with the FLD in the form of train numbers the programme machines expect at certain locations.

In general, it could be argued that the lack of such external representations forces staff to build and maintain their own “picture” of where trains are and that this system is useful in highlighting errors.

It is crucial that practitioners understand the source of information displayed on any replacement to artefacts such as the FLD in order to attach an estimate of its reliability and to diagnose what deviant patterns of information might mean.

SOs are highly practised at coordinating resources of the control panel, the timetable, radio screen and FLD in order to operate and monitor the line, however the upgrade represents an opportunity to improve the mapping between control and displays to make implementing train moves easier to perform and learn. There is considerable physical distance between existing displays and controls. An interface that combined displays and controls into one would make the mapping more direct. Care must be taken not to clutter such an interface, perhaps automatically only showing the information necessary to the current context.

The different interaction strategies currently adopted by SC and SO **during the same incident** indicates that the FLD (and other artefacts) are used in different ways to achieve different (although compatible) goals. Since the roles are to be merged in the proposed upgrade, the challenge remains to design an artefact to replace the FLD that currently caters for these different SO and SC goals and interaction strategies.

Key findings regarding the absence of knowledge in the system to successfully manipulate capabilities of the Connect radio suggest potential changes in the functionality, interface design and/or training would be beneficial. This particularly applies to patch functionality and the way in which talk groups are set up and accessed. Given how important the mimic screen is to the SC as a source of train location, this information should be available at all times, i.e. it should not be lost as a result of necessary interactions with the radio. The train location the mimic screen shows may be improved by showing the movement of trains in a similar way to the FLD (i.e. track direction and finer detail regarding train position). Note: the radio system may not provide this information directly but it can be inferred and also drawn from other sources that do provide it. The application of the Resources Model suggests that the performance of Level 2 SCs may benefit from the support of external representations of plans and histories in the interface of the Connect radio.

The dynamic partitioning of areas of control by Level 2 SCs requires successful routing of communications, e.g. the call made by a TO located on a moving train must be routed to the appropriate SC who has jurisdiction over the area the moving train is currently located within. Some difficulties were noted with the way Connect communications were routed to SOs who currently operate under fixed areas of control (i.e. one SO controls the north end, whilst the other SO controls the south end). The following example illustrates the problem. A call was made by a southbound TO which was dealt with by the north-end SO and then cancelled off the despatch screen. However, the call subsequently resurfaced on the south-end SO's radio as a new call. When the south-end SO picked up the call, the TO was confused as he thought the south-end SO had made the call. This is described by the SOs as a "software fault" but results from the way the radio was used to answer the original call. SOs also pointed out that sometimes train numbers are slow to disappear from one area of the mimic screen as the train moves to another area, causing duplicates to appear for a short while. SOs are particularly sensitive to looking out for duplicates which need to be resolved to maintain an accurate picture of train locations. Such confusions that arise from the way in which Connect works are likely to affect performance in the upgraded system, especially as the control area boundaries are likely to change dynamically rather than remain fixed.

Key aspects about the way the timetable and logbook are used may be incorporated into the design of upgrade equipment. For example, external representations of trains could be highlighted to show reforming opportunities. A system that could capture and represent a history of reforming moves and also provide some validation to the SC to highlight the temporary duplicates that result from reforming the service may also improve performance. The only artefact that represents the number of minutes a train differs from the timetable is the train listings screen. Such a representation is analogous to the flight director interface that indicates to the pilot which direction to steer to maintain a desired flight path (Wright, Field & Harrison, 2000), but may be more useful to a SC if it is coordinated with the type of train location representation currently shown by the FLD.

4.4 Development of practitioners

The change in recruitment policy away from the basis of seniority is driven not just by the need to allow quicker career progression, but also by the evolution of technology. For example, the replacement of remotely stationed signalmen by programme machines ends the signallers' apprenticeship system and means that the pool of SO-related knowledge will no longer be built up from experience of this kind. Of course, practitioners with SO backgrounds and experience as signallers will remain in the control room for some time into the future. However, this projected loss of knowledge may be accelerated by the proposed merging of SC and SO roles simply because Level 2 SCs will implement their own signalling moves, and so the opportunity for sharing such knowledge will diminish. It is also likely that if Level 2 SCs are to be recruited from experienced SCs and SOs, the training required by practitioners from these different backgrounds will be different.

The transfer of "on-the-job" knowledge that is lost from the extinct SC-SO relationship has consequences for the way in which the system learns the changing practice of line control.

Key findings about the relationship that exists between SCs suggest that trainee SCs learn on the job what it is to be an SC. The organisational structure proposed by the upgrade will initially be new for everyone, and the established patterns of behaviour that demonstrate what is expected of new recruits will need to change, in particular with respect to the way in which horizons of responsibility are set to change dynamically as incidents develop.

The separation of Victoria Line and Northern Line control will have at least two implications. Firstly, there will be less experience to draw from in each location since inexperienced practitioners will have fewer experienced colleagues to watch and learn from, and the opportunity to observe incidents being dealt with on the other line will be lost. Secondly, the informal practice of SCs who are responsible for different lines covering for and assisting each other will end, a situation that affects the Northern Line (with one SC) rather than the Victoria Line (with two Level 2 SCs). At the new Victoria Line control room the practice of SCs covering for and assisting each other may be made more complicated by the need to log in to or reconfigure equipment. The type of subordinate-superordinate collaboration observed between SCs of different lines will differ from the working relationship of Level 2 SCs on the upgraded Victoria Line because here the responsibility for line control will be shared.

The upgrade requires a certain amount of high-level strategic decision-making to be transferred from the SC to the SM. Confusion may arise if the new boundaries of responsibility between them are not clear. It is also possible that the shift in activity between the two roles may result in the SM making decisions that are now his/her responsibility in a different way to how the SC would have made them because their respective overall goals remain different. There is an issue regarding whether the new strategic operational decisions the SM must make may suffer if he/she is to remain located mostly away from the control room.

4.5 Development of practice

An examination of the evolution of line control uncovered the trend that organisational and technological change on the Underground has historically been slow and incremental for reasons of cost and safety. Furthermore, the rapid pace of change in technology, such as radio communication, compared to the pace of Underground upgrades was exploited so that lines could be the test-beds for change prior to more extensive roll-out. The Victoria Line upgrade can in a sense be regarded as part of this general trend with its high-profile test of the new Level 2 SC role and the technology aimed at facilitating this organisational change, a test that must succeed if it is to be introduced to other lines. Given the tight coupling that historically exists on the Underground between changes in organisational structure and technology, the redesign of the tools must fit the redesign of the organisation of the work. Crucially, the two aspects must be simultaneously co-designed otherwise a rift will open up between the needs of the practitioners and the capabilities of the tools. For example, a decision to revert to separate SC and SO roles ***after*** the equipment has been designed to facilitate Level 2 SCs is likely to cause usability problems.

Interestingly, the upgrade may represent the limit of the general trend away from distributed and towards a centralised system of control. The further concentration of the tasks of line control amongst fewer practitioners overall follows that trend, but the necessary distribution of control amongst two Level 2 SCs responsible for different sections of the line suggests that further centralisation is unfeasible. Ironically, technological change makes *centralised control* possible ***and*** it helps to accommodate increased service capacity, which in turn fuels a counter-tendency towards *distributed control* in order to cope with the extra complexity.

The key findings and implications for re-design examined here have been drawn from a full analysis (see appendix) that was structured and informed by the framework of DiCoT. The use of that original framework and the adaptations and additions that extend it will now be discussed.

5 Reflections on the use of DiCoT and adaptations to the framework

5.1 Overview

If a phenomenon is pertinent to Distributed Cognition, by its very nature it must be easily observable. This means that a great deal of data is generated by the method within a short time. DiCoT's power as a framework lies in the way it enables an analyst to make sense of large amounts of data gathered from complex domains. A system such as the one capable of conducting line control is so complex on so many different levels that the sheer volume of factors and the relationships between those factors can be overwhelming. DiCoT is capable of addressing this complexity because it provides the analyst with different perspectives on the same data. Because these perspectives overlap with one another, thereby allowing an event to be viewed in multiple ways, the resulting analysis is both exhaustive and affords validation. For example, a radio call taken by an SC has relevance for information flows between the control room and the external world, the properties of the SC as a decision-hub, the physical layout of the SC desk with respect to the arrangement of equipment, the use of the radio as an artefact, the relationship the SC has with external contacts as revealed by language, and the context of the SC's developing skills in dealing with the call together with the history of control room communications.

This strength is also one of its limitations. A complete understanding of any domain is not likely, but without the overlapping perspectives of DiCoT and the volume of data that is generated by using them, the analysis will lack depth. In other words, a "quick and dirty" DiCoT analysis is a contradiction; the exhaustive nature of the work encouraged by the framework is what makes DiCoT useful.

It is consequently easy for the main findings to become lost in the detail of the resulting exhaustive analysis. This detailed resource, however, can be used to draw out a relatively concise narrative, a process that also helps the analyst to re-interpret many of the findings according to the multiple perspectives afforded by the framework.

Since the framework concentrates so explicitly on matters such as the structure of information flow and physical layout, its other great strength is the way it invites the analyst to speculate on how system performance might be affected by re-design.

5.2 Information Flow Model

The Information Flow Model is a good place to start the analysis because the information flows of the system help the analyst to build an early high-level understanding of the work of the domain. By concentrating on the flow between two roles (to the exclusion of other roles), the task of documenting a complex domain becomes manageable. As the individual flows are documented, the actual ***shape*** of the diagram that depicts them helps to identify the key information flow properties, such as decision-hubs and buffers. The difficulty with documenting this is coherence. Because the flow descriptions are so localised and so dependent on each other, the order must be chosen so that one description builds on the next. This is relatively simple for a domain such as the London Ambulance Service (Furniss & Blandford, 2006) because the information flows logically follow a linear pattern from external caller to call-taker to allocator etc. However, the task is not trivial for line control where the pattern of information flows is more like a web.

Another good reason to start with the Information Flow Model is that it “attracts” some of data that eventually becomes relevant to a different model. For example, some data relating to communication as initially documented in the Information Flow Model is more usefully interpreted according to social relationships via the Development of Practitioners Model. Because many aspects of social relationships are subtle it is tempting to misinterpret straightforward communications as belonging to the Development of Practitioners Model, therefore it is helpful to tackle the Information Flow Model first.

Furniss (2004) rightly claims that the proposed structure of the model, i.e. starting with a diagram and breaking this down into summary, detail, further notes and issues, enables the analyst to highlight potential design issues with the way the system currently works and improves understanding as the analyst uses the model. This applies to the Physical Model and the Artefact Model and is the reason the new Development of Practitioners and Development of Practice models follow the same basic structure.

5.3 Physical Model

The Physical Model naturally follows the Information Flow Model because it addresses the positioning of the artefacts and actors just introduced and provides a tangible context for the information flows already described. The different levels of room layout and desk layout help to highlight different system properties that are determined by physical arrangement. For example, the important horizon of observation for different practitioners and their orientation with respect to each other is only apparent from the room level layout. Focusing at desk level helps the analyst to choose which desks are relevant for the study. In this case, SC and SO desks were chosen, rather than the SOI desk, because of the merging of SO and SC roles proposed by the upgrade. The documentation of all equipment at desk level helps to set a context for the further narrowing of focus required by the Artefact Model.

5.4 Adapted Artefact Model

The sheer number and individual complexity of artefacts used by practitioners is overwhelming. However, by the time Information Flow and Physical Models have been tackled, a few artefacts emerge as being key. The order of models is therefore essential to guard against an irrelevant in-depth analysis of artefacts that do not impact greatly on the system.

The diagrams that serve as the starting point for each key artefact are not easy to design. The difficulty lies in deciding the type and quantity of detail to depict. Furniss (2004) chose to show the high-level layout of data types in screen representations, for example in Figure 11 (pp 65). The Connect radio mimic screen, FLD and timetable do not lend themselves to this type of representation. In all these artefacts some representation of what the data ***consists of*** is just as important as the layout. For example, the mimic screen layout (figure 5) is influenced by the number of trains that exist in a track zone. With the timetable (figure 6), the challenge is to depict properties such as the diagonals of constant time whilst abstracting out the detail of actual data. The FLD is such a unique blend of visual data that it makes little sense to reproduce it other than in its raw form, hence the annotated photograph of figure 16 in the appendix section 9.3.1.

The basic Artefact Model helps the analyst to understand at a relatively high-level what the physical interface consists of, but it does not help to examine in detail ***how the practitioner interacts with it to conduct activity***. Therefore, the Artefact Model has been adapted to include a more detailed examination of the practitioners' interactions with key artefacts by applying the Resources Model (Wright et al., 2000). This description, in terms of the use of abstract information structures and whether these are represented externally or internally, helps to envisage design opportunities aimed at helping the practitioners coordinate such representations. Once the analyst has a basic understanding of the components and layout of the interface, the practitioner-artefact interaction can be examined in terms of the abstract information resources of the Resources Model. The six resources as explained in detailed by Wright et al. are: plans, goals, possibilities (or affordances), history, action-effect relations and states. Generally, a complex activity (such as performing the signalling operations that implement a strategic change to the service in line control) involves all these resources. The aim of the analyst is to ascertain the full set of abstract resources utilised by the practitioner in the context of a particular activity, and to identify their concrete realisations in the interface. Where they do not exist externally in the interface, by inference they must exist in the mind. Of particular interest are those distributed resources that exist partially in the world and partially in the mind. For example, the stream of FLD lights that represent trains approaching a track location where they are to be turned constitutes an externally realised list of goals. However, since the train numbers associated with that list of trains are not displayed on the FLD, the full goals resource is manifested in a coordination of the external FLD representation and an internal representation of associated train numbers as determined from a variety of other sources (e.g. Connect radio despatcher screen, train listing screen, other control room staff etc). Structuring the analysis in this way helps the analyst to understand what combinations of tools are required in the conduct of activity and to identify those aspects of performance which will both be affected and potentially improved by re-design.

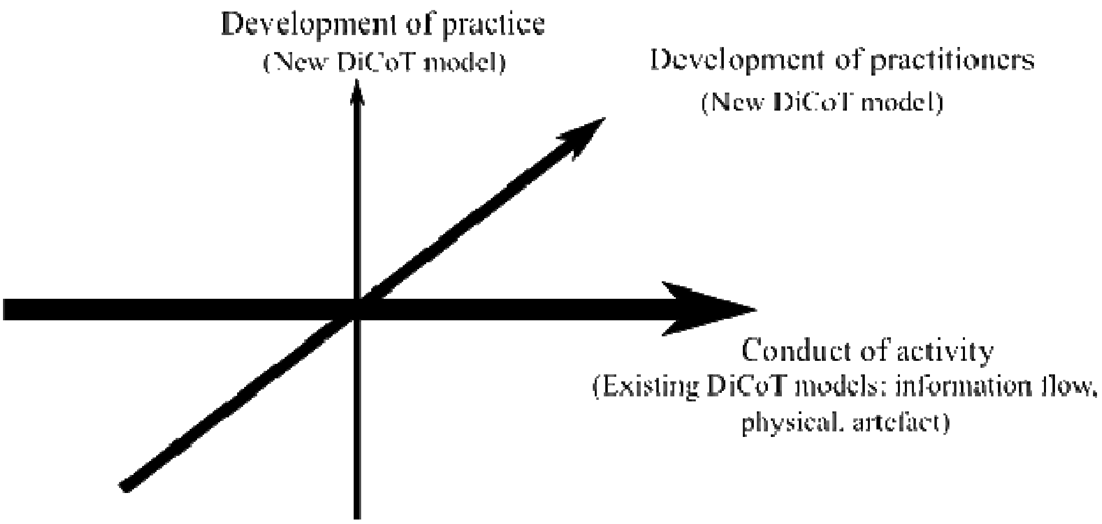
6 Additions to DiCoT

6.1 Overview

The three existing models of DiCoT between them help to describe a system ***as it is*** in some depth. However, a description that addresses how a system has come to be the way it is can help to identify how knowledge develops over time (i.e. how the system learns) and the important trends that affect the long-term evolution of the practice. These extra dimensions can aid understanding of ***why a system is the way it is*** and further illuminate implications for re-design.

The additions to DiCoT originate from the insights of Hutchins (1995), in particular surrounding the way cognition associated with any human practice is a product of the cultural processes that have developed over time. A moment in human practice can be viewed as an intersection of three developmental sequences: the development of practice; the development of practitioners; and the conduct of the activity itself. Furthermore, every moment of human practice is simultaneously a part of these developmental sequences. Figure 9 represents a moment of human practice and is adapted from a version of Hutchins' original diagram (1995 pp 372). The thickness of the arrows represents the rate of change at which states in that dimension are changing. The diagram helps to show how the models of DiCoT fit into a moment of human practice.

Figure 9: Moment of human practice (adapted from Hutchins (1995 pp 372))



Following Hutchins (1995) in relating this model to line control, the conduct of the activity can be seen as the activity of control room staff interacting with each other and with a set of tools to monitor and maintain the service to timetable, for example in response to an incident, and is measured in minutes and hours. Changes in this dimension occur rapidly and interaction between the elements of the system is intense, however residual structures may survive beyond the end of the tasks resolving a particular incident, such as voice recordings, marks in logbooks, timetables and computer records, and in the memories of the control staff.

Such an experience at the level of conduct of activity also represents opportunities for individual practitioners to learn “on the job”. The development of a member of control room staff is measured over years and is an accumulation of the knowledge learned in other roles spanning an entire career.

The setting of line control activity evolves over time as solutions to common problems are saved in the artefacts and representations of the job and in the social organisation of control room staff. This development of practice is measured over decades. It is important to understand that the same processes that constitute the conduct of activity produce changes **simultaneously** in both the individual practitioners and in the social, physical and mental dimensions of the context of the practice.

As Figure 9 illustrates, an analysis based on existing DiCoT focuses only on the ***conduct of the activity.*** The structure of the development of the practitioners and the development of the practice models that extend DiCoT will now be examined in more detail.

6.2 The Development of Practitioners Model

The development of practitioners here is concerned with how the system learns through the developing knowledge of practitioners. This knowledge is accumulated over the span of practitioners’ careers and is partly a function of the way work is socially organised, i.e. through the relationships between roles in the system. The analysis starts with a high-level summary and a diagram that represents the current social organisation of the work. According to Handy (1985 & 1995) organisational culture is determined by the relationships that exist between structure, power and communication. For example, line control has elements in common with the Role Culture category (Handy, 1985 & 1995) where roles and role relationships are fixed, people can move in and out of these roles, and communication follows lines of command. The diagram in Figure 7 therefore reflects a hierarchical structure although this is by no means universal; other types of culture will reflect different types of structure. Each key relationship between roles is then described in greater detail. Following the structure adopted by Furniss & Blandford (2006), each description is further examined in terms of issues that relate to design implications.

The structure of social relationships for an organisation may be formally described (e.g. in a management chart) and this description may represent a starting point for the analysis at this level. Certainly, such a description highlights the nature of relationships deemed important by powerful members of the organisation. However, the analysis should question this perspective when gathering data and be alert both to how formal relationships differ in practice and whether any other important informal relationships exist between practitioners. Also such a formal description of organisational structure may reveal the absence of relationships between practitioners, posing the question why. The organisational structure in line control is hierarchical but, for many cultural and operational reasons, is not maintained in the same rigid way as the military setting described by Hutchins (1995). Again, this fact generates many questions about how and why the hierarchical relationships differ between the two contexts. The fact that line control hierarchy is not maintained through the authority of rank leads to sources of potential conflict that could be affected by organisational or technological change. Describing each relationship exhaustively in turn helps the analyst to build a Development of Practitioners diagram where lines of control and overlapping areas of responsibility can be depicted. Another key aspect is a description of the goals of practitioners and how these might differ in emphasis, even when these goals appear the same. For example, the SC and SM are both motivated to maintain a stable service with few delays, but the SM's emphasis is on the financial implications of delays, whilst the SC is concerned with operational matters of safety. The difference in emphasis may be subtle but the implications for the relationship between the two roles are crucial, particularly in terms of potential conflict. The diagram together with the descriptions can further be analysed to draw out insights crucial to any change of the structure. For example, the fact that currently only one SC controls the Victoria Line, in contrast to the upgrade proposal of two SCs, naturally focuses the analysis on the relationship between SCs. A straightforward examination of the current structure would seem to suggest that an analysis of this relationship is impossible. However, SCs in the current set-up ***do*** have relationships with each other: during the brief handover; during training; and between the Victoria Line and Northern Line SCs. Furthermore, these relationships illuminate the boundaries of responsibility that exist while one SC is in control of the entire Victoria Line, a concept which must be re-examined in the new upgrade structure. The analysts should be alert to this type of informal, potentially undocumented relationship because it can lead to important insights. For example, the informal relationship between Victoria Line and Northern Line controllers is especially interesting because it exists between two practitioners of comparable experience (i.e. not trainer-trainee) and where the ultimate aim is not to hand over responsibility within a short period of time (i.e. not the shift handover). As such it provides a tantalising perspective on how Level 2 SCs will join forces in the future.

The diagram and the individual relationship descriptions together provide a snapshot of the way the work is currently organised. Equally important to how a system learns over time, however, is a description of how practitioners develop, i.e. what they know from related past roles and how that knowledge is useful in the current structure. An overview description of the pool of career knowledge that feeds into the organisation takes into account the ways in which the different roles are recruited and are likely to progress. Such a description may reveal trends about the propagation of such knowledge over time, which affect the way in which activity is currently conducted. For example, the traditional recruitment policy for SOs resulted in practitioners with a valuable store of information about how signals are implemented in the field, a fact that can be exploited by SCs who know that SOs are a likely rich source of such information. Drawing out such trends enables assertions about changes to such a state of affairs, for example that the change in recruitment policy, automation of signalling, and merging of SC and SO roles are all likely to accelerate the loss of traditional SO career knowledge.

6.3 Development of Practice Model

The development of practice here is concerned with the co-evolution of the artefacts and tasks over the long term. A choice must be made as to the period of time the analysis should cover. Hutchins (1995) demonstrated that the properties of the tools and representations currently used in navigation are directly related to the evolution of these artefacts over centuries. However, for practical reasons the analyst must choose the period of time that has the greatest relevance and impact on the focus of the study. This study necessarily concentrates on the history of the Victoria Line even though line control is influenced by the operation of earlier railways, such as the first public passenger-carrying underground railway, the Metropolitan Line, which opened in 1863. The development of the practice of line control immediately prior to the opening of the Victoria Line was deemed necessary to describe because it ***directly influenced*** the choices for new technology and organisation instigated for the first time on the new Victoria Line. Of equal importance to the temporal scope of the analysis is the scope of the practice. The temporal scope is represented by the horizontal scale of the timeline, whereas the scope of the practice is represented by the vertical depth of the diagram, i.e. what are the limits to what is attended to at any one point in history? The London Underground is particularly fascinating as a domain in that it consists of the parallel evolution of loosely related but autonomously controlled lines. The evolution of each line influences the evolution of every other line. The timeline diagram could therefore be expanded vertically to depict all these influences. A choice was made to limit the scope purely to the Victoria Line for practical reasons, but the analyst should remain aware that such wider influences could exist and may be important. For example, the way in which the separate lines were used as different test-beds was an economical and less risky means of exploiting the rapid evolution of radio communication, and epitomises the incremental nature of change on the Underground. However, it resulted in a fragmented system that eventually required standardisation through Connect.

Structurally, the analysis starts with a high-level summary and a timeline diagram that represents key moments in the history of the technology and organisational structure. Each timeline represents a separate strand of evolution, e.g. driver-controller communication technology. To a certain extent, the challenge facing the analyst is to extract from the raw data (interview and historical sources) those groups of technology and organisational structure that should be represented as a single timeline. Again, the previous DiCoT models, in particular the Artefact and the Development of Practice models, help to identify key aspects of the domain. The analyst can then inspect the historical data for the antecedents of those key aspects, grouping them together functionally and identifying the points where major change occurred. The evolution represented by a single timeline highlights questions regarding the transition between successive technologies and structures, such as what were the properties and limitations of a technology that motivated major change? The depiction of parallel timelines placed against a time scale helps to pick out any important dependencies or relationships between them. Sometimes a new technology or organisational structure is introduced which does not simply replace existing aspects of a domain. For example, TrackerNet and, indirectly, Connect are both examples of technology that provide train location information, but although train listing technology pre-dates these technologies, it is not superseded by them. The design of the timeline diagram forces the analyst to make such distinctions explicit and encourages analysis of why this situation exists. For example, TrackerNet, Connect and train listing technologies coexist because they show a variety of types of train location information derived from a variety of sources. Each timeline is then described in greater detail taking into account its significance, the reasons that contributed to major change, and the dependencies that exist between timeline components. Relationships that exist between organisational structure and technology can be identified from moments in history where major changes occurred at the same time. These relationships are of particular interest to HCI because they demonstrate at a high level that the design of technology is inextricably linked to the way in which people must orientate to, and interact with, that technology. From the diagram and the detailed descriptions, trends and issues relating to re-design implications are drawn out, i.e. how do any proposed changes relate to the past development of key technologies and the organisation of work? Do the proposed changes fit into established trends of the development of practice or do they represent a seismic change?

7 Discussion

Section 1.1 of the introduction examined the scope of DC and suggested that as a theory it does have the breadth, depth, concepts and unifying language to apply to diverse aspects of a complex domain. The discussion will now reflect on the extent to which this is true in the context of this study by asking two questions:

- As an approach, does DC possess the scope required to inform design?
- Does DC possess the scope required to extend and adapt the DiCoT framework?

7.1 The scope of DC to inform design

Furniss (2004) demonstrated that DiCoT can be used to assess the impact of design changes to the London Ambulance Service (LAS) system especially in terms of information flows between practitioners and physical layout. A claims analysis design rationale was performed to assess the pros and cons of altering the configuration of people and artefacts in terms of the functional consequences for system performance. In performing this exercise, Furniss (2004) claims that the most promising design ideas in terms of improving system performance in the LAS are incremental rather than ones that involve major structural changes. However, the proposed changes of the Victoria Line upgrade represent a fundamental over-haul of the entire system, in terms of new room layout, new equipment and new organisation of the activity of line control. Therefore, despite the many implications for change that a DiCoT analysis of line control has been able to generate, in its current form the framework cannot go further to bridge such a wide gap between analysis and design.

Upton et al. (2008) argue that since ethnomethodological approaches such as DC and Activity Theory are primarily descriptive, they have limited power to predict the impact of change, and cannot inform the visual design of system representations. It is true that DC focuses on understanding how an existing system ***currently behaves*** rather than how it ***should behave***, however its theoretical scope is rich enough to provide a bridge between analysis and design. Hollan, Hutchins & Kirsch (2000) demonstrate the potential of DC to yield fertile design ideas, and more importantly to ***drive design*** towards what truly matters in human-machine interaction. For example, the finding that pilots use perceptual strategies based on the spatial position of a conventional air-speed indicator's needle rather than simply reading numerical information, can be incorporated into the re-design of such an instrument whilst also exploiting the potential of digital technology. The result is an artefact that remains compatible with the way in which practitioners interact with existing technology, potentially enhancing performance in a way that is impossible if the conventional airspeed indicator is merely reproduced in digital format.

The value of an integrated approach with DC as its foundation as advocated by Hollan, Hutchins & Kirsch (2000) is that it offers a ***consistent*** view of socio-technical systems, which establishes a starting point and direction for design. By contrast, Upton et al. (2008) argue for a mixed model approach that aims to apply different frameworks and techniques to different aspects of the analysis of a domain based on their respective strengths. The difficulty with this approach lies in integrating different frameworks so that a coherent process emerges to link analysis and design, and although the approach succeeds in generating visual designs, a potential cost is the skill and effort required in choosing and combining perspectives. Upton et al. (2008) use DC in a focused way to understand why a work system has its current organisational and physical configuration. However, they do not appear to exploit DC's full potential in describing how the coordination of representations of information constitute the activity of work, and how this understanding might then be harnessed to ***drive*** design.

In summary, although DC theory has the potential to inform and drive design, more work needs to be done to develop the framework of DiCoT to facilitate the bridge between analysis and design. In particular, how can DiCoT be adapted to link its ability to generate implications for design with the user-centred techniques that generate actual designs? The work of Hollan, Hutchins & Kirsch (2000) offers a potential starting point for answering this question.

7.2 The scope of DC to adapt and extend DiCoT

DC has proved to be a rich and adaptable source of ideas for the adaptation and extension of DiCoT. The concepts used to adapt the DiCoT's existing Artefact Model to include the cognitive strategies for coordinating different internal and external representations are drawn from the Resources Model developed by Wright et al. (2000). The concepts used to extend DiCoT to include the new models, Development of Practitioners and Development of Practice are drawn from insights made about the evolutionary nature of human practice by Hutchins (1995).

However, how effective are these DiCoT adaptations and extensions that have been informed by DC theory? How useful are they in contributing to the understanding of a complex domain such as line control? One way to answer these questions is to examine how DiCoT was applied in this study to shift handovers. Section 1.2 highlighted that shift handovers in nursing are instrumental in enabling practitioners learn what it is to become a nurse. It is clear from the key findings that shift handovers in line control do not hold the same significance. This is so clear simply because after the shift handover was examined through all the models of DiCoT, only the Information Flow Model was able to illuminate the process. In other words, the Development of Practice and Development of Practitioners models that both deal with the way in which the system learns had little to add to the analysis of shift handovers. Instead it is the social relationships of line controllers (particularly between Victoria and Northern Lines), the hierarchical organisation of roles, the pool of career knowledge and the evolution of the practice over decades, that are the major influences on learning what it is to become a line controller. The extensions to DiCoT enabled these findings to be made.

7.3 Conclusion

Upton et al. (2008) apply their mixed model analysis to the high volume manufacturing of electronic components, a domain where the scale and rapid pace of change may warrant such an approach. Certainly, DiCoT has so far only been tested in smaller-scale domains where the pace of change is slow, and so applying it to larger enterprises that are subject to rapid change is a logical next step. It is likely that as a result of such a test, DiCoT will again require adaptation and extension, however this study has shown that the framework is adaptable and that DC is a rich resource of concepts for achieving this. DC is not just a theory that affords straightforward examinations of how people interact with physical, tangible manifestations of a work environment, although it does this very well. It undoubtedly has limitations, for example, Upton et al. (2008) claim that it is weak at describing the technical aspects of cognitive systems. However, what DC provides is a sophisticated and fertile ***way of seeing*** and as such, despite its limitations, there are no limits as to what it can usefully be applied to in a work environment.

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9 Appendix

This section contains a full analysis of the Victoria Line control room undertaken using the DiCoT framework. The analysis is organised according to the five models of DiCoT: Information Flow; Physical; Artefact; Development of Practitioners; and Development of Practice.

9.1 Information Flow Model

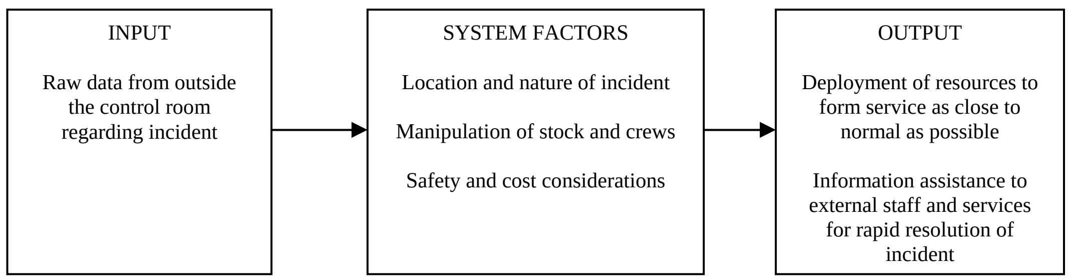
Following Furniss & Blandford (2006), this level of the analysis begins with a high-level diagram, which summarises the raw data input, the main system factors, and the target output in order to provide a reference frame for the focus of the analysis.

The high-level representation is decomposed to examine in greater detail how information flows between system components (i.e. the actors and the tools they use) and how these components are integrated to achieve system behaviour. Furniss & Blandford (2006) recommend two flow diagrams: the first to concentrate on describing each branch of communication; the second to focus on the important information flow properties of the system. Each diagram is further broken down into summary, detail, further notes and issues. The proposed structure is designed to enable the analyst to highlight potential design issues with the way the system currently works and is also meant to improve the analyst's understanding as he/she uses the model.

9.1.1 Overview: High-level input-output diagram

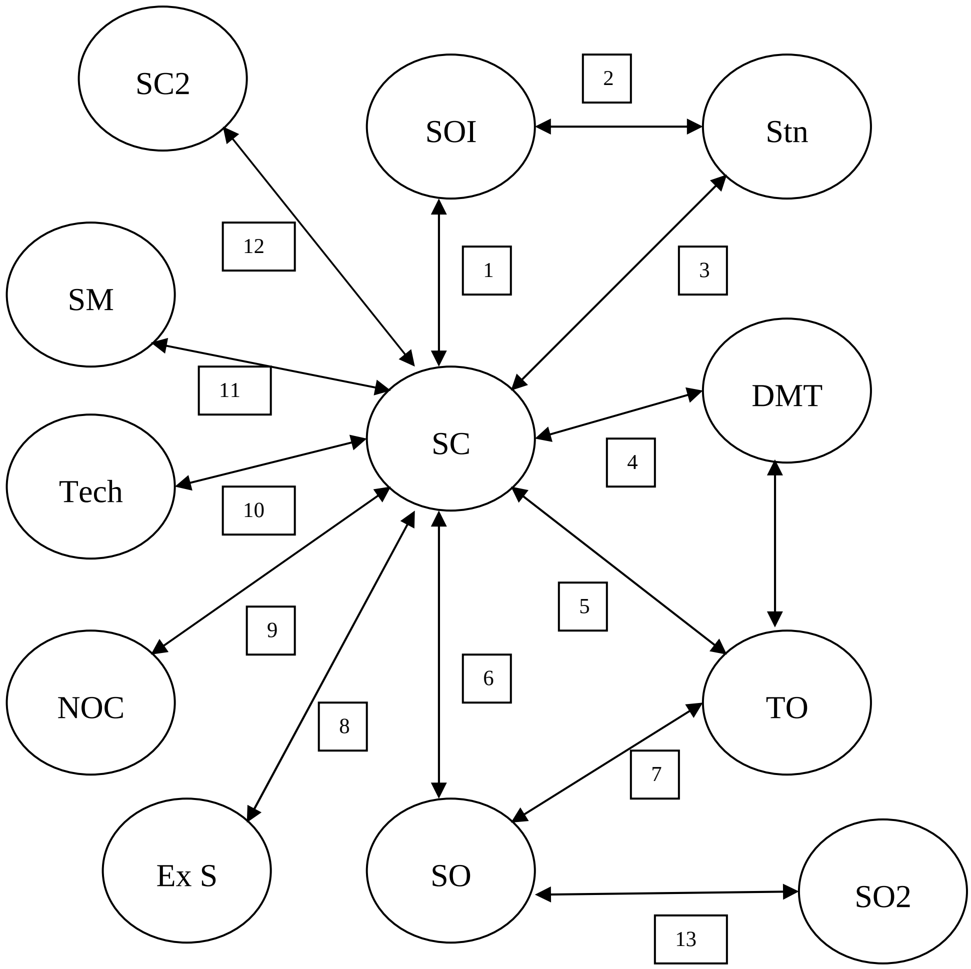
This diagram shows the main input and output information to the system of Victoria Line control that forms the focus of this analysis, in particular the task of recovering from an incident to produce a safe and stable service with the minimum of disruption.

Figure 10: High-level input-output diagram



9.1.2 Flow of Information: Communication channels

Figure 11: 9.1.2 Flow of Information: Communication channels



Key

Letter	**Actor**	**Role**
SOI	Service Operator Information	Information assistant to service controller
Stn	Station staff	Supervision staff based at a station
SC	Service Controller	Responsible for strategic decisions to maintain service, and traction current.
SC2	2nd Service Controller	Acting as relief or assistance to 1st SC
DMT	Duty Manager Trains	Manages train operator crews
SM	Service Manager	Overall manager of line control
Tech	Technicians	Diagnoses and repairs faults to trains
NOC	Network Operations Control	Central communications for all lines
Ex S	External services	Includes ERU (Emergency Response Unit) and BTP (British Transport Police). Also FRC (Fault Report Centre)
SO	Service Operator	Responsible for tactical signalling operations

SO2	2nd Service Operator	Acting as relief or assistance to 1st SO
TO	Train Operator	Operates train

Table 1: Description of communication branches

Branch	Comment
1	**<u>Service Operator Information (SOI) - Service Controller (SC)</u>** SUMMARY The SOI supports the SC by listening to what he/she is doing and then updating relevant stations with the appropriate information relating to an unfolding incident. DETAIL The communication between SOI and SC is rarely explicit. For example, if the SC is dealing with a passenger alarm on a southbound train that must remain at Oxford Circus, the SOI will then inform station staff at stations further south on the line that will be affected by the delay. The SOI will listen out to developments to that incident in order to propagate relevant and timely updates to the affected stations until the incident is resolved. The SC and SOI may occasionally communicate explicitly with each other regarding station matters, for example overcrowding at a station – a situation they will both have visual access to via CCTV. The direction of communication can be 2-way but generally, the SOI receives information indirectly from the SC and does not give information directly to the SC. The SC also listens out for announcements the SOI makes in order to know which stations are currently aware of the situation. FURTHER NOTES The SOI is highly skilled at picking out the salient information from the SC's other communications and will translate this to what the station staff recipients need to hear. The SOI will also listen to other conversations in the control room to make sense of unfolding incidents – this is a general skill that all control room personnel learn through practice. ISSUES • The communication may be affected by the noise level of the room which increases significantly during an incident. • Both explicit and implicit communication between SC and SOI is directly affected by the physical layout of the room. The SOI sits behind and above the SC – they both face the front of the room. Consequently, the SOI can see the SC and what he is doing, but the SC normally has no face-to-face contact with the SOI. I observed a situation where the SC gave an instruction to an SOI who was not sitting behind him – the situation was only noticed when the SC asked for verbal confirmation that the instruction had been carried out.

2 **<u>Service Operator Information (SOI) - Station</u>**

SUMMARY
The SOI generally speaks directly with station staff via the Connect radio system in turn in order to update them about a delay that will affect them.

DETAIL
The SOI can communicate with the station in a number of ways:

(a) Directly via Connect radio or telephone:
The Connect radio screen allows the SOI to choose a particular station to relay information to station staff based there. The station staff will then use the PA system to make announcements to passengers – note: the information relayed to passengers by these announcements will be tailored to their needs. For example, they may be given further advice such as to use a different line. This communication method is most common if there is an incident causing delay.

(b) Directly via PA announcement:
The SOI may choose a platform to make a direct PA announcement to passengers regarding a specific incident but in practice this is rarely done.

(c) Indirectly via pre-recorded PA announcement:
One of the tasks an SOI has to perform is to deliver half-hourly recorded messages about the state of the line. This message can be recorded via either a physical phone or the touchscreen telephone. Standard messages, such as “Normal service with no delays” can be selected then propagated to each station in turn.

The SOI can also maintain awareness about events at a station visually via CCTV screen. Through the same screen the SOI uses to choose a platform for PA announcement the SOI can choose a CCTV camera to view. This is useful for example to spot developing overcrowding problems. The Victoria Line is unique in that every station except Pimlico has an interchange with another line or overground rail, and the passenger walkways are designed to be short. This means stations and platforms can get overcrowded very quickly as problems develop on other lines.

FURTHER NOTES
The main Connect radio screen shows information about where particular trains are (i.e. in the vicinity of certain stations). However, to ensure that the SOI does not mistakenly attempt to contact a train, the train buttons are greyed out. The SOI may only contact stations via the Connect radio screen.

ISSUES
Use of the PA system has an order of precedence: Station then SC then SOI. This order of precedence is enforced, i.e. if the PA system is in use by the SC, the SOI is unable to use it. If the system is in use by a higher priority user, the new announcement will not be heard. Use is indicated by a

	red square on the PA screen next to a particular station's platform (northbound or southbound). The SOI often checks to see if the SC is using the PA system before attempting to use it. The CCTV camera selection screen marks some cameras as "F1" meaning faulty. Some of these marked-as-faulty cameras are actually operational – SOIs (and SCs) just remember which ones are operational.
3	<u>**Service Controller (SC) – Station**</u> SUMMARY Typically station staff contact the SC in the event of an incident that is safety-critical and/or is likely to cause delays to the service. Once an incident is unfolding, the SC may contact station staff to provide or request updates or to issue instructions. DETAIL The SC communicates with station supervisor staff via either the telephone (to a fixed telephone receiver at the station office) or via the Connect radio (to a mobile handset carried by staff as they move about inside stations). (a) Telephone contact is made either via the touchscreen telephone (which has pre-programmed numbers and is recorded) or the manual telephone back-up (which also has pre-programmed numbers and is not recorded). (b) Connect radio contact is made via the despatcher screen. The SC can also make PA announcements directly at a station platform, using the same method as the SOI (see (2) above). In practice, this is rarely done – platform announcements are left to station staff or the SOI. FURTHER NOTES • Certain pre-programmed contacts on the touchscreen phone are fixed line, enabling the receiver of a call is immediately aware of who is making the call (i.e. caller ID functionality). These contacts are marked in green. However, the station staff contacts are ordinary lines – showing only as an incoming call with no caller ID (marked in blue). • There is a "cut in" facility on the touchscreen telephone. If, for example, the SC wishes urgently to speak to someone who is engaged – he/she will be able to cut directly into the conversation. This is vital for safety-critical activity. • If an outside caller calls and the SC is already using the phone, that caller hears a continued ringing tone (i.e. not an engaged tone). • An emergency or "mayday" call is highlighted on the touchscreen telephone in red and has a higher pitched ring tone. By taking that call the SC automatically cuts off the existing call. There are occasional false alarms with the system falsely interpreting calls as mayday calls. • The incoming call notification on the Connect radio screen flashes

	red for an incoming mayday call and has an audible notification. • The SC can use the telephone as a buffer by putting calls on hold. • Functionality regarding access to talk groups and individual contacts is managed according to control room staff usergroups. ISSUES • The SC does not know upfront what the most immediate method of contacting station staff is. He may try the telephone but this will be fruitless if no-one is in the office. He may try the radio but this may be switched off. • SCs point out that caller ID on the phone is useful but not available in all instances. • Since the Connect radio can be used to contact staff who may be out of the office, it is seen as the most useful method of communication of the two methods. • One SC I observed and interviewed explained she was keen for improved flexibility and functionality regarding the Connect radio. The radio has capability for group calls or 1-to-1 calls. However, radios in stations are not personally assigned to individual members of staff – rather each person picks up an available radio handset from a pool. It would therefore (in the current organisation) be useful for the SC to make a group call to a station, rather than to a particular handset, because a group call will be attended to by any station staff holding a radio that is switched on. Group calls to stations are disabled for the SC usergroup. The SC therefore resorts to 1-to-1 access, dialling 5-digit numbers that correspond to radios held at that station. A physical directory of these numbers is permanently kept on top of the bank of screens that surround the SC desk, however looking up the numbers is time-consuming and inefficient because the SC may try several numbers until she finds one that answers. She will then jot down the number (and the name of the person currently holding that radio) in the logbook as a reminder to herself and to others who may take over from her. If a station supervisor calls on the radio, she will often ask for his number to save time in subsequent communications regarding the same incident. The Connect system is capable of saving numbers although the use of this functionality was not observed. The SC can log out from the despatcher screen and log in as SOI usergroup to gain access to the station talk groups but in practice this is not done (partly because the SOI login has access restrictions such as not being able to contact individual trains, and partly because it is inconvenient). In summary the despatcher system is capable of setting up useful station talk groups (and other talk groups that are not location-based) but the SC was unaware of the functionality. Even if this functionality is available, if it is tied to control room user groups there is an issue of the inconvenience to log in and out of roles to access it. • Being able to attach aliases to numbers would provide caller ID (useful to SCs) however if this functionality is available it is not

	used because radios are not personally assigned to individuals. • The SC also expressed a requirement to be able to select pre-set-up talk groups and/or individual 1-to-1 numbers, for example, those relating to three stations and an engineer that may be affected by an incident. A call to this temporary set of talk groups would reach all relevant parties. As the incident developed she would be able to select and deselect talk groups as necessary, thus increasing the flexibility and efficiency of communications. This functionality is available using the patch facility, but does not appear to be in use, i.e. the system does not have the knowledge to make use of the capability. This is a problem of training and/or visibility/usability of the functionality the system provides. • Flexible and easy-to-use talk groups would make the Connect radio the primary means of communication to stations, leaving the phone as a back-up. The view was also expressed (by more than one SC) that a more powerful radio system would alter the working relationship between station staff and SCs thereby improving the quality of the service delivered. For example, if the radio system became a more dominant form of communication, there would be no excuse for having handsets switched off and staff would not feel compelled to remain physically tied to the office. As a result of a reliance on the telephone, some SCs complained that some station supervisors on the Victoria Line tend not to be proactive, preferring to remain in the office. Examples include supervisors needing to be cajoled into action such as helping with a sticky train door or demanding to be updated about situations developing at their own station! This type of relationship between technology and the social organisation of work is examined in more detail in section 9.5.
4	**<u>Service Controller (SC) – Duty Manager Trains (DMT)</u>** SUMMARY There are three DMTs for the Victoria Line: one based at Seven Sisters (closest station to Northumberland Park Depot where trains are stored); one based at Brixton (for crew stepping back – see below); and one mobile ("blue light") DMT who can attend the location of incidents. The SC will typically need to communicate to a DMT to confirm crew availability in advance of any change that may need to be made to the service. Contact is made either via telephone or Connect radio. DETAIL • In response to an incident, the SC will make strategic decisions about how to change the service, which at a tactical level may be translated into any of the following "moves": - reform a train (i.e. changing the number/ID of the train) - cancel a train - reverse a train early - hold a train in sidings or depot These moves obviously affect the TO. If for example a train is to be reformed, the physical train will enter a new pattern on the timetable perhaps requiring it to remain in service for longer than it was

	originally planned to do so. A TO requiring a break or coming to the end of his/her shift will need to be taken into consideration. For this reason, moves are planned to coincide with a change of driver (either because he is due a break or the shift is over). The DMT is often consulted to ensure that there is a TO available to pick up the newly formed train and to relay instructions to the TO regarding the move (e.g. to change the train ID information as necessary). • An ex-DMT explained that DMTs are not strictly responsible for guaranteeing that TOs pick up trains on time but their presence on the station platform or in the office located near the platform is meant to "smooth" the changeover of trains. However, a chain of command does run from SC to DMT to TO – for example, I observed a situation where a train was one minute late departing and the DMT phoned the SC to request that the delay be "booked" on the summary of incidents sheet. The SC speculated that this was probably as ammunition for the DMT to discipline the driver who may have been making a habit of turning up late for pick-ups. (Note: for more information on the social relationships that exist in the system see section 9.4 on the Development of Practitioners Model). • Stepping back – this procedure is only in place for turning trains back on the northbound at the south terminus Brixton and is designed to speed up the process. At Walthamstow where stepping back is not used, the TO arrives at the station, disembarks the cab, and walks to the far end of the train to enter the other cab, an activity that is scheduled to take up to four minutes. Stepping back involves another TO waiting at the rear-end of the platform to take the train northbound as soon as the current TO vacates. The relief TO is the TO of the train that arrived two trains previously. This practice cuts the scheduled turnaround to one minute and allows TOs to take comfort breaks. SCs communicate closely with the Brixton DMT to coordinate moves to the service and see stepping back as an opportunity to increase the set of moves open to them. FURTHER NOTES See branch 3 for detail about the means of communication via phone and Connect radio ISSUES See branch 3 for detail about the means of communication via phone and Connect radio
5	**<u>Service Controller (SC) – Train Operator (TO)</u>** SUMMARY The SC will communicate directly with the TO regarding incidents that are safety-critical or otherwise have an impact on the service. For example, a TO may contact the SC to report a faulty train (e.g. doors not opening or closing properly). The SC may deal with this incident by communicating with other personnel in the system and will contact the TO regarding updates/instructions. The Connect radio is the primary means of

	communication, although TOs indirectly communicate with SCs (and others in the control room) via the train itself (i.e. its position and ID/number). The tunnel telephone is a separate communication channel between TO and SC purely for safety-critical incidents. DETAIL • Usually it is critical for the SC to know where the train is located to know what to do next during an incident. The Connect radio despatcher screen shows approximate train location updated in near real-time. The SC will use this as the most reliable indicator of train location (the train listing and fixed line diagram providing other clues), however the despatcher screen is never relied upon totally for two reasons: (i) It is not accurate – on the Connect Radio screen sections of track are labelled according to the station they are located closest to. An individual train appears on the screen at a labelled location but this does not mean the train is at this station. (ii) It is not 100% reliable – the information on the screen is dependent upon the train ID information entered as the TO logs onto the train radio. Mistakes are made, especially when a driver changes trains and forgets to update the ID. For these reasons, the SC usually asks the driver to confirm his location. • Train position is communicated in four ways: (i) Connect radio system (see above) (ii) Identra: At the point of picking up a new train, the TO uses an “Identra” dial in the cab to set the route/destination information. This information is relayed to the control room, combined with timetable information such as the train number, and presented to the SC (and SOI and SO) on a train listing screen. This information is also potentially inaccurate and unreliable (again because of potential data-entry errors made by the TO), and all control room staff consider it superseded by the Connect radio system although it shows the number of minutes a train is late (information not supplied via Connect radio screen). SCs do not tend to use it – it is partly obscured by a clipboard (perhaps on purpose to avoid confusion). The SC can update train ID info via the train listing screen (e.g. a train number 477 denotes a default assigned by the system where the train ID is unrecognised). It used to be the responsibility of the SC to change this (although anyone in the control room can do so), but no-one bothers to update this information any more. (iii) A signal through the track. When something is on a section of

	track, this information is relayed to the control room and is presented to all control room staff on the fixed line diagram (FLD) as a red light to indicate position. Again the information is potentially inaccurate, in that anything on the track may result in a signal (e.g. a tin can). Also a faulty section of track may light up even if there is nothing on it. The information displayed on the FLD is not directly combined with train ID information. The information is provided at a coarse level of detail – single lights on the FLD correspond to varying lengths of track which are not represented exactly to scale and may or may not equate to the length of a train. Consequently it is not simple to infer the number of trains from a continuous area of lit-up track on the FLD. (iv) TrackerNet. This is like an electronic version of the FLD and shows train positions on a track layout diagram, but unlike the FLD combines train position and train ID. The information that drives TrackerNet comes from the same information source that supplies the train listing screens. TrackerNet suffers from similar problems of unreliability and inaccuracy as the FLD but it may also fail completely. Often the only indication TrackerNet may not be working is that screen freezes, i.e. the information does not update. The SCs do not tend to use this source of information. In practice, the SC may use a combination of different sources of information to increase his/her confidence in the location of a particular train. FURTHER NOTES • Relevant information regarding a faulty train and subsequent delays is relayed when necessary from TO to passengers via cab radio. • The SC will make a general group call to TOs regarding an incident. For example, a train with a security problem stuck on a platform at Walthamstow (the north terminus of the line) meant that only one platform was available for southbound change-overs. Since stepping back is only in operation at Brixton (the south terminus), this incident had the potential for causing a considerable delay. Therefore the SC put out a general radio call to all drivers approaching Walthamstow requesting a quick turnaround. After the incident was resolved, a similar general call was put out thanking drivers for the quick turnaround and to communicate that the problem was over. In general, every message that informs personnel that a problem has occurred is mirrored with a message to inform that the problem has been resolved. • The TO may also communicate with the SC via the tunnel telephone. In an emergency, for example, where a person is on the track or under the train, the TO may pinch together two copper wires running horizontally down the tunnel wall (an action that takes off traction current) and attach a handset which allows him/her to communicate with the SO via a special dedicated telephone. The SOs tunnel telephone handset is located near the traction control

	panel and is used only for this purpose. There are special procedures the driver must follow in the event that the tunnel telephone does not work. ISSUES • The unreliability and inaccuracy of train position is a general issue with existing line control room technology. The Northern Line (a more complex line) employs the use of Positive Train Identification (PTI) – train IDs are transmitted to the control room and displayed on the equivalent FLD. Even PTI is not 100% reliable due to signal interference and Northern Line SOs make use of a dedicated CCTV screen simultaneously showing images from four cameras positioned to provide a visual check of the train ID shown on the front and reverse train cars. PTI will be available for Victoria Line upgrade trains (09 stock). However the incomplete picture regarding train position is not generally a problem for control room staff who are highly skilled at picking up the cues they need from separate displays to build awareness of where trains are. They know when to give weight to a piece of information and when to ask confirmation from TOs and each other. They actively seek to maintain this awareness even when the service is running normally. They exploit the separate and redundant nature of the different train location sources in order to spot discrepancies. • Group calls to "all drivers" are actually to all Underground staff who have a radio set tuned in to receive calls from the SC. The radio system prior to Connect was not enabled to make 1-to-1 calls, only group calls. Some drivers with experience of this system prefer the group calls because they can build an awareness of what is happening elsewhere on the line even if the call doesn't directly concern them. • One SC claimed that group calls to drivers on a particular section of track would currently not be useful because of the uncertainty surrounding train location information, i.e. such a group call may erroneously include or exclude TOs that are on the boundary of a zone arbitrarily defined by the system. SCs word their messages to TOs in such a way as to define groups of recipients, e.g. "Message for all drivers on the northbound approach to Oxford Circus…" The upgrade control room technology is capable of splitting the line into areas of control so that SCs can communicate exclusively with TOs on their patch. It is envisaged that the improved train location certainty that this change requires would be delivered by new upgrade technology .
6	**<u>Service Controller (SC) – Service Operator (SO)</u>** SUMMARY The SC and SO remain in close communication regarding the movement of trains. The SC will delegate implementation of their strategic moves to change the service to the SO. The SO will pass information regarding the location of trains and any message from TOs regarding minor incidents that

	may affect the service. The main means of communication is verbal, although in certain circumstances a telephone will be used in which case the conversation is recorded. DETAIL The SO's primary role is to monitor the service and to operate the signals when required. As a matter of routine they record the service (by noting down the arrival and departure of trains at two locations on the line) There are usually two SOs on duty and the work is partitioned physically between north and south ends of the line. They maintain a more detailed picture of the location of trains and the state of signals than the SC and the SC will often ask them first to confirm the location of a train. Where minor incidents may impact on the service in the form of delays, the SO passes the information up to the SC. SOs make minor adjustments to the service to bring it in line with the timetable without involving the SC, for example, holding a train at a station to even out gaps in the service. In the event of a more serious incident, the SC communicates the moves he wishes to make and the SO implements them. For example, an SC may decide a train running late on the northbound should be reversed early at Seven Sisters so that it's on time on the southbound. The SO will manually operate the normally automatically controlled signals at Seven Sisters to make that change. Despite being within easy earshot, the SC will occasionally use a fixed line on the touchscreen telephone to relay such instructions. All conversations using this line are recorded for legal reasons. There are no rigid rules regarding the circumstances in which the SC should make use of the phone: • If the room is particularly noisy, the SC will use the phone. • If the SC is busy, he/she may choose not to use the phone, i.e. it may be easier to shout over to the SO than to operate a phone, especially if the SC is making lots of calls via radio and phone. • The phone may be in use already. • Some SCs prefer not to use the phone because they feel it formalises the communication too much – "Sometimes it's just nicer to talk to someone." • For safety-critical information the SC always uses the phone. Doing so transfers responsibility to the SO, i.e. there is now a legal record of an instruction relayed and received. The use of the phone in this instance acts as an extra reminder to the SO that this instruction must be acted upon. FURTHER NOTES The control room previously had a glass partition between SOs and SCs, i.e. ensuring the phone was used to relay all messages. This was removed as unworkable because it had a detrimental effect on the communication between them and probably increased the workload of the SC in terms of making calls. The glass partition would have reduced informal communication considerably – banter in the control room is common and lively, especially between SO and SC (see section 9.4 on the Development

	of Practitioners Model for how this influences learning within the system). The SO is officially just the implementer of strategic decisions made by the SC. However, in practice the activity relating to line control is negotiated between them depending on their relative experience. An inexperienced SC was observed to monitor the situation while two highly experienced SOs manoeuvred the trains without delegation. ISSUES Enforcing use of the phone for communication between SC and SO has pros and cons. Pros are: • Certainty – neither party is in any doubt whether to use the phone or simply talk. • Exhaustive record of all control room communications between SC and SO. Cons are: • Difficulty – the phone handset must be lifted to the ear. I witnessed busy SCs holding both radio and telephone handsets to their heads at the same time. Solutions to this include headsets, an intercom system separate to the phone, or recording by default all conversations in the room. • Inhibiting valuable informal communication. Of course, as part of the upgrade it is proposed that the SC and SO roles will merge making these issues irrelevant. However, the current communication between the two roles highlights what might be lost in terms of a record of the distributed decision-making that leads to changes in the service, and the explicit on-the-job transfer of knowledge that results from conduct of the activity. Also the built-in redundancy that results from having extra people monitoring the line for problems will reduce if a consequence of merging roles is fewer staff in the room.
7	**Service Operator (SO) – Train Operator (TO)** SUMMARY There are three types of communication: (i) TOs contact the SO to relay minor incidents relating to their train. The SO may contact a TO, for example to request that the train be held in a station to even out gaps in the service. The means of communication is Connect radio. (ii) The SO also authorises safety critical moves, such as a TO passing a signal at danger which is known to have failed. This is done via one-to-one calls on Connect, a recent development, since on other lines it is still usually achieved by fixed line telephone, i.e. signal-post telephone. (iii) Again, the TO communicates indirectly with the SO regarding train position.

	DETAIL (i) TOs can contact either SC or SO but are trained to contact the SO for minor incidents such as: a passenger emergency alarm (many of these turn out to be false alarms generated accidentally or by children) or doors failing to close. (ii) ***Only*** the SO can authorise these moves. The SC cannot do this because the SO is regarded as the ultimate authority on train location. (iii) Train position is represented on the FLD, train listing and Connect radio screens, of which the FLD and the Connect radio is the most used. ISSUES The assignment of the safety-critical element of this communication to the SO rather than the SC highlights the SO's greater attention to train position. The proposed merging of SC and SO as part of the upgrade will result in a Level 2 SC role that must therefore maintain a greater awareness of train position than the current SO, whilst also carrying out the decision-hub type activities of the current SC. For FURTHER NOTES and ISSUES relating to train position technology see branch 5.
8	**Service Controller (SC) – External services** SUMMARY In the event of a major safety-critical incident the SC may need to liaise with external emergency services: ERU (Emergency Response Unit) and BTP (British Transport Police). Also in the event of faulty infrastructure equipment, the SC must report the failure to the FRC (Fault Report Centre) within 15 minutes or cost penalties are imposed by the infrastructure company MetroNet. The means of communication is touchscreen telephone. DETAIL The important numbers are pre-programmed. ISSUES SCs have set reporting priority sequences they must use, which change depending on the situation. For example, in the case of a passenger emergency alarm, the Service Manager is contacted before NOC (see branch 9) because the NOC will then immediately contact the Service Manager requesting further information. However, in the case of a "one under" (someone hit by a train), the Service Manager is low on the list of priority contacts after the NOC. SCs remember these sequences but it may be useful to have an external checklist as a reminder. Often, the incidents unfold very quickly and it is easy to forget for example to contact FRC, the only contact associated with a set time limit.
9	**Service Controller (SC) – Network Operations Centre (NOC)** SUMMARY NOC is a central facility for London Underground that collects and

	disseminates information regarding the state of all lines. The SC contacts the NOC to report a delay with the service via the touchscreen phone. The SC can see updated reports on the state of all lines (including the Victoria Line) via a Simlink screen. DETAIL Information is sent to Simlink in the form of messages that flash on the screen until the SC acknowledges them. The messages must be acknowledged with a certain time limit or the NOC will contact the SC. This system was implemented in response to the King's Cross disaster where controllers directed passengers to King's Cross without being aware of the fire. Even "Good service" messages must be acknowledged. Once acknowledged, all messages remain on the screen for reference, except "Good service" messages. The SC may delegate the contacting of NOC to the SOI who also has access to a Simlink screen. ISSUES Some SCs see this as a necessary irritation. Perhaps therefore only service delay or safety-critical messages need to be acknowledged. Simlink occasionally goes down – this is noted in the logbook and relayed to NOC to inform them that the SC can neither see nor acknowledge messages.
10	**Service Controller (SC) – Technician** SUMMARY Technicians are responsible for diagnosing and repairing trains to keep them in service. They will make recommendations but the SC (and ultimately the SM) has the final say about whether a train should remain in service or not. There are two technicians: one based at Vauxhall and one based at Seven Sisters. Contact is via Connect radio. DETAIL SCs attempt to keep trains in service whenever possible. They have access to a document called Defective In Service Instructions (DISI) that provides advice about whether a certain faulty train necessitates being taken out of service for repair or not, however despite several occasions observing SCs dealing with technicians and faulty trains, I did not see SCs consult it. One example illustrates the dilemma facing the SC. An SO spotted a gap in the service and the problem was suspected to be a slow-running train. Victoria Line trains operate automatically (they pick up codes from the track that dictate the train's speed), so if a train is running slowly often even the TO will not know especially if the speed difference from normal is not great. However, even a slightly slow-running train will cause a delay to build up. The SC contacted a technician to rendezvous with the train – this can be difficult depending on whether the technician is already busy, or if the train is a long way from either Vauxhall or Seven Sisters. The time to

	technician rendezvous, the time to diagnose the fault, the current impact on the rest of the service, the likely impact on the service if the train is removed for repair, and the availability of TOs all influence the SC's decision. ISSUES The Connect radio numbers for the technicians are written on the screen surround to the despatcher screen. SCs dial these five-digit numbers in order to make contact. The radio system allows the numbers to be input as easy-to-use touchscreen aliases but this functionality has not been exploited either because it is unknown or too difficult.
11	**<u>Service Controller (SC) – Service Manager (SM)</u>** SUMMARY The SM needs to be aware of all major incidents and delays, either by observing directly in the control room or by phone if he/she is based in the separate SMs' office. SMs also have access to the electronic Summary of Incidents sheet. DETAIL The SM will often request updates via phone regarding ongoing incidents. The SC will automatically contact the SM for major incidents and delays (see branch 8). The SC makes a separate entry for each delay of two minutes or over in the Summary of Incidents sheet. When these build up, the SM will phone the SC to walk through the sheet and request any clarifications. If the incident is major the SM will leave the office and come to watch the control room first-hand (usually standing just behind the SC on the middle tier). They may make suggestions and participate in line control activity, but generally leave the SC to do his/her job without interference. ISSUES The spreadsheet occasionally is unavailable. The back-up is a paper sheet to which the SM has no direct access from the office. In this situation phone contact between SM and SC increases especially during busy incidents.
12	**<u>Service Controller (SC1) – Service Controller (SC2)</u>** SUMMARY There are four situations where SCs communicate with each other: (i) During a shift handover. (ii) To cover for each other during comfort break (iii) To assist each other during incidents (iv) Training (i.e. between senior SC and trainee SC) This is predominantly face-to-face verbal communication. The shift handover also involves a separate hand-written page in the logbook. (ii)-(iv) is not covered in section 9.4.

	Shift handover occurs three times a day at approximately 06.30, 13.30 and 19.30 to coincide with non-peak hours. SOs, SCs and SOIs change shifts at roughly the same time. DETAIL **Shift Handover**: In general, the handover is informal and rapid especially if the line is quiet. If it's straightforward it lasts no more than 2-3 minutes. The longest one observed was 10 minutes. The process can be split into three phases: preparation phase, handover phase, and completion phase. **Preparation phase:** In the hour prior to shift handover, SC1 writes on a separate page in the logbook (a few pages ahead to leave room to write other entries for the remainder of his/her shift). There's a separate paragraph for each handover entry, and it is written in capitals (for legibility). The handover sheet contains all those outstanding out-of-the-ordinary pieces of information that SC2 will need to know in order to control the line, i.e. those facts that would prevent or hinder the SC in the activity of line control if they were unknown. The first few entries relate to ongoing unresolved situations brought forward from the last handover. Some of these entries have appeared in the handover for months or years (e.g. CCTV cameras marked as defective). One regular entry is a reminder to SC2 to check that the timetable is open at the right section. Looking up a train at a particular time on the wrong day is an easy error to make so this is always checked. One example of an entry specific to a shift is "Notification of single-end feeds" due to engineering tests on a particular section of track. Ordinarily a section of track is fed current from either end by two sub-stations. The single-end feed causes a reduction in current – if too many trains draw current from this section of track at once, the power will trip out resulting in potential delay. This entry doesn't modify the behaviour of SC2 in any way. It merely **prepares** SC2 for a possible outcome to an unusual state of affairs on the line. If the power does trip out, SC2 will be ready for it and will request the power to be immediately reinstated, and may bring the engineering tests to an end. The entries are deliberately short (often in abbreviations/shorthand) – they contain only as much detail as is absolutely necessary. This type of communication requires a shared understanding as to what terms mean and what their implications are. The entries tend to be relevant for an entire shift rather than detailing transient problems. A problem with a train for example isn't mentioned in the handover but it may be referred to verbally. A problem with the monitoring kit they use is always mentioned in the handover. If it is feasible, SC1 will make an extra effort to get the service to a stable state prior to the end of the shift. On one occasion the SC1 reformed a special service back to timetable after a major incident – "You need to get it

done as quick as possible anyway, but it's nice to have things wrapped up before you knock off – it gives you a good feeling."

Handover phase: When SC2 arrives, he/she will glance at the FLD – gaps indicate problems. They are skilled at assessing the state of the line quickly from this. The noise level of the room is another clue – the control room can be noisy during non-busy periods but this is down to banter and laughter. When the room is busy, the room is noisy but there is no laughter – "the atmosphere is different – you can just tell". They may also have a sense of the state of the line from TFL website and their own journey in. They do not check in at the SMs' office.

When the line is quiet, SC1 runs through each entry in the handover sheet verbally with SC2. SC2 may ask questions for clarification. They often point to and look at the FLD as well as the handover sheet. Sometimes they refer back together in the logbook for extra detail (for example, regarding a problem train).

When the line is busy SC1 will be too occupied to run through the handover sheet. SC2 will pick up the situation from observing SC1 and listening to conversations. Ordinarily, much of the operational verbal communication inside the room and over phone/radio is repeated, either requesting clarification or confirmation, so SC2 tends to pick up the gist of problems quickly. There is a back-up touchscreen phone and a training handset attached to the Connect radio despatcher to listen in to conversations if necessary. Ordinarily, SCs tend to deliberately "tidy up" sub-problems in an incident so that they have one less thing to deal with. This practice helps to simplify the handover and gives SC2 a clear point in the sequence of activity to start taking over. SC1 may give short summaries/updates on unfolding problems at opportune moments between calls (sometimes letting the caller ring until he/she is ready to answer).

Completion phase: At some point, SC2 will feel confident enough to take calls. SC1 will continue assisting until it is clear SC2 has the situation under control. Unless it is very busy, this is usually signalled when SC2 takes a call or takes control of the timetable (there's only one on the desk). There is a sense that SC1 supports SC2 past when their shift is officially over if required, although SCs are also keen to leave after a long shift and will rely on their colleagues being skilled enough to take over quickly. When the line is busy the written handover sheet may not be run through at all but it is there as a reference should SC2 need it later.

ISSUES:
The handover is informal but effective and generally seamless. When it is busy, a successful handover is achieved by both SCs integrating their activity with an emphasis on the following:

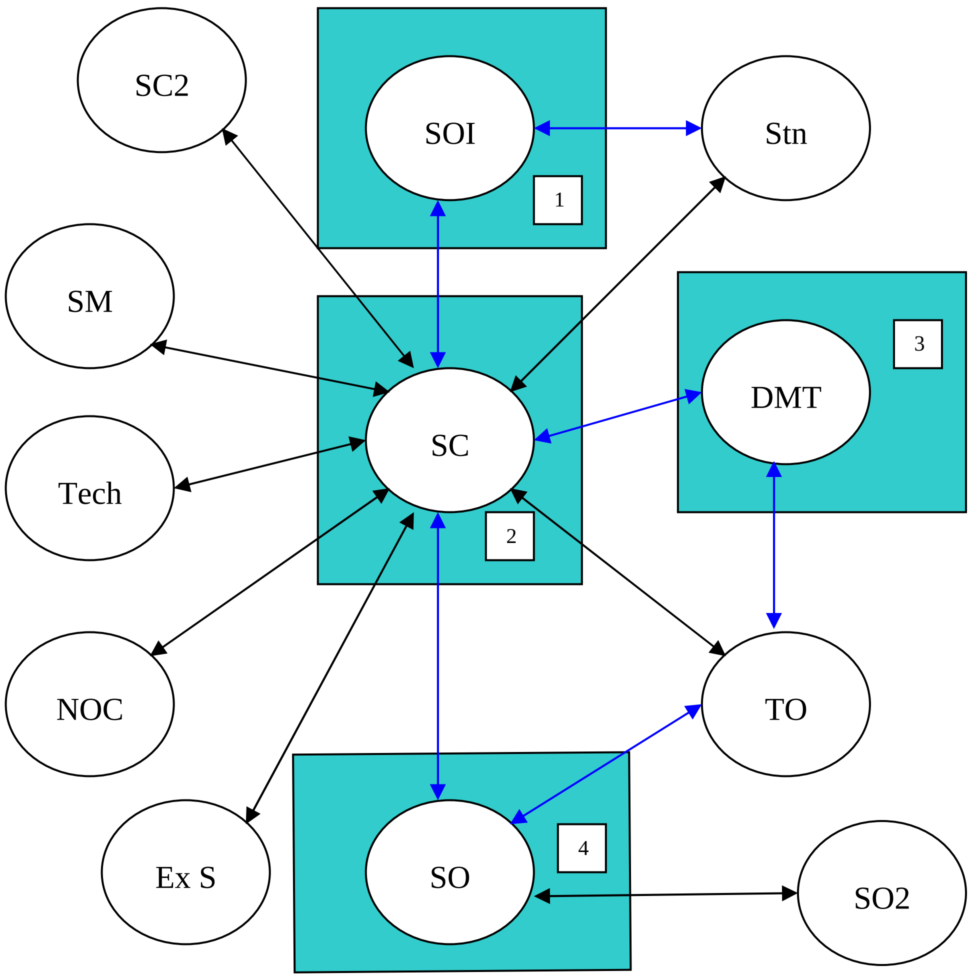
- A concentration on the salient information (no extraneous details)
- A shared understanding of how problems develop and should be solved
- Trust in each other's abilities

	• A clear understanding of the boundaries of responsibility, i.e. only one SC is currently responsible for the Victoria Line – this makes it simpler to hand over responsibility The following factors may disrupt this smooth handover process: • A necessity to deal with tasks not directly related to line control (e.g. logging in to systems – no control room staff have personal logins currently but the upgrade technology does.) • Under existing plans, the upgrade line can be split when busy into up to seven different areas of control – the temporary nature of boundaries of responsibility may cause confusion at handover.
13	**Service Operator (SO1) – Service Operator (SO2)** SUMMARY There are normally two SOs on duty to control the signals and monitor the line: one takes responsibility for the north end (north of King's Cross to Walthamstow Central), the other takes responsibility for the south end (north of King's Cross to Brixton). When it is quiet, one SO can easily cover the whole line. The fact that SOs are used to cooperating during a normal shift in this physically partitioned way makes the handover similar to normal activity and less pronounced than the handover between SCs. This distinction applies to other forms of SO-to-SO communication such as training and covering for each other during comfort breaks. Only communication during the shift and at handover will be dealt with in this analysis. DETAIL **During shift:** North end and south end SOs organise their work so as to constantly check with each other the location of trains. The work involves noting down the departure and arrival times of trains at Seven Sisters (north end) and Victoria (south end). The paper booking sheet used for this is a snapshot of the timetable at these locations. They use this, the FLD, the Connect radio despatch screen (one each dedicated to the relevant section), the train listing screen (one each switched to the relevant section) and each other to build up awareness of where trains are. They look out for duplicate trains (usually a mistake by the TO). **Shift handover:** The handover does not involve a handover sheet. However SO1 will point out unusual information on the booking sheets. For example, when a normal timetable moves to a special service, different sheets are used until the timetable can be resumed. The special service is a reduced number of trains numbered 001, 002, 003 etc. The special service is swapped back to a normal timetable at the same place on the line – always at Seven Sisters because it's near the train crew depot where the required TOs are located. SOs work in a similar way to SCs to support each other during busy handovers. However, the handover is more straightforward even during busy periods because their role is predominantly a monitoring one, i.e. less reactive to unfolding situations. For example, they do not have to respond

	to many phone/radio calls. In response to a major incident at King's Cross, for example, the SC may decide to operate two independent loops either side of King's Cross. The SOs' job in this instance is to implement that strategic decision but once the initial signal operations have been worked out they are repeated until the incident changes or is resolved. For relatively uncomplicated sections of track where reversals are possible (e.g. at Highbury and Warren Street) and engineering works are planned, an auto-reverse facility can be invoked which doesn't require manual intervention. In summary, **the nature of the job itself** makes handover relatively simple. ISSUES: The handover between SOs is smooth and simple in the existing system but the challenge for the upgrade system is to preserve this situation. Proposed changes such as merging SO and SC roles, changing the permanent nature of the north/south split of responsibility and introducing system logins may cause disruption.

9.1.3 Flow of Information: Overview of key flow properties

Figure 12: 9.1.3 Flow of Information: Overview of key flow properties



Key

Letter	**Actor**	**Role**
SOI	Service Operator Information	Information assistant to service controller
Stn	Station staff	Supervision staff based at a station
SC	Service Controller	Responsible for strategic decisions to maintain service, and traction current.
SC2	2nd Service Controller	Acting as relief or assistance to 1st SC
DMT	Duty Manager Trains	Manages train operator crews
SM	Service Manager	Overall manager of line control
Tech	Technicians	Diagnoses and repairs faults to trains
NOC	Network Operations Control	Central communications for all lines
Ex S	External services	Includes ERU (Emergency Response Unit) and BTP (British Transport Police). Also FRC (Fault Report Centre)

SO	Service Operator	Responsible for implementing signalling operations
SO2	2nd Service Operator	Acting as relief or assistance to 1st SO
TO	Train Operator	Operates train

Table 2: Description of the Main Flow Properties

Property	**Comment**
1	<u>**Service Operator Information (SOI): Filter and buffer**</u> SUMMARY The SOI filters information picked up from the SC (and elsewhere in the control room) and tailors it for either station staff or passengers. The SOI also acts as a buffer between the SC and staff and passengers located at the station. This dual role focuses information where it is needed in the form it is needed and relieves the SC from having to disseminate this information directly, thereby improving the performance of the system. DETAIL **Filter:** The filtering is a skilled activity that involves tuning into those pieces of information that are relevant to recipients at stations and using those pieces of information to construct a concise and clear message. The SOI must understand from the SC (from amongst all the SC's utterances) how the incident will impact passengers at relevant stations. The message is delivered to all stations that will be affected by an unfolding incident. The key pieces of information elicited are: • What is affected by the incident – train, track or station? • The location of the incident. If the incident relates to a train, the SOI needs to know where the train is and where it is heading (i.e. northbound or southbound) • When the incident is resolved – this will generate an update message that needs to be delivered to all those stations already contacted. Note: the details of the incident are unimportant. For example, a train may not be running. This is all that counts. The fact that it is not running because there is a dog loose on the train without a lead is not relevant to the message (although the SOI also attends carefully to the details in order to pick up a sense of when the incident will be resolved). **Buffer:** The SOI acts as a buffer by relieving the SC from having to inform the public (either directly through PA announcement or indirectly via station staff). This means the SC can concentrate on purely the operational aspects of the incident without having to convert information for a different audience. The SOI also pre-records messages which are retrievable via radio by station staff answering passenger queries about the service. This activity acts as a buffer by encouraging station staff to consult these messages rather than contacting the control room directly.

	FURTHER NOTES • The filtering process converts the raw information supplied by the SC into a **consequence**. How will this affect the service and therefore paying passengers? • The role of buffer in protecting the SC from unnecessary communication relies on the SOI doing his/her job with the absolute minimum of direct communication with the SC. ISSUES • It is rare that the filtered information disseminated by the SOI will reach the passenger directly, i.e. it is usually repeated by the station staff to become an actual announcement. Also to access up-to-date information delivered by the SOI, the passenger must either attend to the announcement or ask station staff to access it again. • A consequence of the proposed role-merging of SC and SO is that certain verbal SC communications to the SO (e.g. regarding the reforming of trains) will be lost and therefore unavailable to the SOI to act upon. • Currently, the SOI attends mainly to one SC. In the proposed upgrade, during an incident two Level 2 SCs will each responsible for different sections of the line. This architecture allows the SCs to work in parallel to resolve the incident (or incidents) whereas in the current system one SC is forced to work serially. This may make the SOI's task of overhearing relevant information more difficult.
2	**<u>Service Controller (SC): Decision Hub</u>** SUMMARY The SC is the central role in line control, dealing with most of the flows of information entering from outside the control room regarding incidents and subsequently orchestrating the responses aimed at resolving those incidents. DETAIL The SC is the main strategic decision maker in the line control process and is at the hub of the following communication channels: other control room staff (i.e. with SOI and SO); other London Underground staff external to the control room (i.e. DMT, TO, SM, NOC, station supervisors, and technicians) via phone or radio despatcher and electronic equipment; and other external services (i.e. FRC, ERU and BTP) via phone. FURTHER NOTES The SC has a number of representations that aid their decision-making: • The Connect radio, the FLD, and the timetable combine to give likely locations of particular trains. Train location can be checked through the SO and/or TO. • The FLD gives an indication of the state of the line and the sources of potential delays.

	• With its representations of sidings, reverse points, signals and the depot, the FLD illustrates what moves are possible. Note: the layout is not a truly accurate representation. It is simplified to aid decision-making related to the movement of trains. • The timetable acts as a target – something the SC should aim for in order to achieve a normal service. This is colour-coded to aid perception. • The timetable acts as a resource to highlight moves. SCs mark up the timetable to show when certain trains are due a change of TO and where they are when this opportunity exists. • The Defective In Service Instruction document aids decision-making by detailing the conditions under which a train may be kept in service or not. • The track and signal diagrams book is the most accurate map used by the SC. It shows up-to-date real-world structures that are represented in simplified form by the FLD with the addition of traction current information. This is colour-coded to aid perception. • The logbook is a record of all significant decisions the SC has made and a reminder of exceptions that apply to the normal operation of the line. It helps the SC to know what decisions are possible at the current time. • The clocks positioned at several places on the FLD give the SC easy access to the exact time. The clocks are radio-linked across the network so that all staff operate to the same time reference. The 24-hour format aids calculations regarding delays and record taking (i.e. the SC simply copies the numbers rather than interpreting the time from an analogue display). • The Connect radio despatcher and touchscreen telephone screens convert contact numbers to representations of objects or people to make communication easier. For example, the touchscreen telephone converts an internal contact number to a green box labelled “VIC SIG” so that phone contact with the SO is easier to achieve. See section 9.3 on the Artefact Model for more details about the Connect radio despatch screen, the timetable and the FLD. The SC relies on the SOI, the SO and the DMT to act as buffers in order to concentrate on the main role of line control. ISSUES The representations could be enhanced to improve decision-making capability. Here are some examples: • Understanding exactly how the FLD, timetable and Connect radio despatcher screen are combined to give train location may suggest improvements. Once a train is identified it could be “tagged” on the FLD to show what control room practitioners think it is.

	• Alternatively, the Connect radio despatcher screen information regarding train ID could be superimposed over the FLD to make comparisons easier. Note: the timetable information is superimposed on the FLD already in the form of train numbers the programme-machines expect at certain locations. • The DISI document could be electronically available to aid decision-making. At present it is a paper document not kept on the SC desk. Experienced SCs may know this document intimately but it may aid newly trained SCs to have a searchable/intelligent electronic version of the information easily to hand. The same applies to the rule book. The paper versions would still need to exist as back-up. As the track and signal diagrams book is required for safety-critical decisions regarding traction current, it is not recommended that this be made available electronically because SCs need to be familiar with looking up information in the physical format that is **always available**. • The Connect radio despatcher system could be improved to more easily allow SCs to set up and manipulate the talk groups they need, and to make sure that dialling regularly required contacts is replaced with caller ID representations that match objects and people. In the proposed upgrade structure, there will no longer be just one central SC as decision hub. This has implications for the flow of information: • How will external contacts be routed to the appropriate SC? If SCs are given responsibility for control over one section of the line, then the routing of **some** radio/phone calls can be based on where the contacts are, e.g. station staff at relevant stations and TOs on trains. Obviously trains that can move across the boundaries of SC responsibility will need to be located with precision and certainty. The upgrade rolling stock will have reliable Positive Train Identification (PTI) that improves train location information (provided the TO has input the correct train ID information). However, during the transition to upgrade technology, a mixed fleet of existing and upgrade rolling stock will be operated, a situation that has implications for maintaining awareness of train location. Even if train location information is reliable and accurate, information about a faulty train that moves between sections necessitates a form of handover (such as exists between sectors in air traffic control) – a situation that does not arise with a single decision hub. This leaves those external contacts that are not easily associated with physical section of line, e.g. emergency services, SM, mobile DMT etc. How will these contacts be routed? How will the information that's relevant to other SCs be propagated? • Traction current control is highly localised, relevant to specific sections of track. However there is currently one traction current panel and since the activity of controlling it is highly safety-critical, decisions regarding its use must be accountable, visible to other SCs, and clearly controlled (i.e. who has access and under

	what circumstances?) • The structural change means that SCs will be tactically implementing strategic decisions regarding the line without necessarily needing to articulate those decisions. Therefore if more than one SC shares control of the line, information about those decisions must be communicated. This might be achieved verbally or through making the moves clearly visible to others.
3	**<u>Duty Manager Trains (DMT): Buffer and decision support</u>** SUMMARY The DMT acts as a buffer between the SC and TOs by providing a single point of contact regarding crew availability and decisions regarding reforming the service. The DMT also acts as a decision support by suggesting options open to the SC through a process of negotiation. This dual role relieves the SC from having to make further communications directly with TOs to ascertain availability and assists in the process of changing the service, thereby improving the performance of the system. DETAIL **Buffer:** Crew availability is in the ideal world a case of referring to shift details and the timetable. In the real world, crew availability is subject to changes not reflected in documents available to the SC (e.g. TO illness, lateness, mistakes etc). It is the DMT's job to be aware of these changing issues and communicate them to the SC **when necessary**. SCs are aware of how the system is planned to run, e.g. that a TO is due to pick up a certain train, but not down to the details of which TO and exactly how many TOs are available at a particular time. The DMT also disseminates information about a proposed set of moves to reform the service to the relevant TOs (i.e. one conversation about train number changes becomes several as each TO may arrive for duty at slightly different times and places within a station). ISSUES In the proposed upgrade where SC and SO roles merge to form two Level 2 SC positions, the locally based DMTs will negotiate with the SC responsible for the relevant section of line. However, it may be that information arrived at through these conversations must be propagated when the SC boundaries of responsibility change dynamically. Decisions about reforms to the service affect the whole line, so SCs may negotiate a sharing of the work such that only one of them will handle reforms. Since the train crew relief point is based at Seven Sisters on the north section of the line, this is likely to be the north-end SC. However, an additional train crew depot is planned for Brixton on the south section, so this may change.
4	**<u>Service Operator (SO): Filter, buffer, decision-support and early-warning</u>** SUMMARY The SO acts as a filter/buffer, converting SC instructions about moves

	into actual signal operations. The SO acts as a buffer between the SC and TOs. The SO acts as a decision-support by suggesting strategic moves to change the service. The SO acts as an early warning system by spotting potential delays and problems on the line. DETAIL **Filter/buffer:** The process governing the conversion of SC strategic decisions into signal operations appears to be automatic – the hand movements are skilled and highly practised. The experienced SO does not ponder or discuss how the move should be made. The activity between SC and SO is tightly coupled so that the instruction becomes action as if the move was being executed by one person. This coupling relies on shared understanding between SO and SC about where trains are, something that can only be achieved by both parties actively maintaining this awareness, This awareness however is required at different levels of detail. The SC needs to know that a train is approaching the point at which the move is to be made. The SO needs to know with greater precision where a train is in order to coordinate the signal operations associated with the move and will follow its progress on the FLD with greater attention. This delegation of the monitoring task allows the SC to attend to other things. **Buffer:** TOs can contact either SC or SO but are trained to contact the SO for minor incidents such as: a passenger emergency alarm (many of these turn out to be false alarms generated accidentally or by children) or doors failing to close. Also in fine-tuning the service in order to keep it to timetable, the SO will contact a driver asking him to wait in a station before proceeding in order to even out gaps in the service. **Decision-support:** More experienced SOs often suggest moves to the SC particularly if the SC is inexperienced. Often the move occurs as a result of a negotiation between SO and SC. In understanding what the SC wants to achieve, the SO may suggest elegant implementations that the SC hadn't thought of. However the SC has the final word and may reject suggestions on the basis of other knowledge the SO is not aware of. For example, an SC rejected a suggestion because it didn't fit in with what she had learned following a conversation with the DMT. **Early-warning:** SOs are valued by the SC for their skills in spotting potential delays and problems. For example, an SO diagnosed track failure in a particular section from the way the FLD was lit. ISSUES: In the proposed upgrade SC and SO roles will merge, thus removing the benefits detailed above. The new SC role must give more attention to monitoring the line if the same level of performance is to be achieved. This may cause conflicts of priority if the SC is to also to remain a decision-hub fielding information from various sources. The signal operation implementation of strategic moves will therefore need to be simple, demanding the lowest possible cognitive workload to achieve. Plans to increase the number of SCs overseeing separate parts of the line

	are aimed at distributing the high-level responsibilities that one SC has now. Interestingly, if the interface to control signals is to change, it will entail current SOs, for whom the manipulation of signals is practised, to have to learn a different interface to achieve the same actions. An interface with a closer conceptual fit to the way signal operations are achieved now will potentially favour current SOs. An interface with a closer conceptual fit to the way SCs conceive of strategic moves will potentially favour current SCs. Of course, the merging of the roles may result in improved efficiency where strategic decisions are translated seamlessly into signal operations by a skilled operator. The decision-support and early-warning properties which would be lost by the merging of roles may have implications for the way the system learns.

9.2 Physical Model

Following Furniss & Blandford (2006), this section of the analysis is split into two levels: the layout of the room; and the structure of individual desks. These levels are chosen because they have important properties that influence information flow and therefore the performance of the system. The structure of both SC and SO desks are examined to reflect the importance of the proposed organisational change that sees these two roles merging.

The physical layout of the system is examined in terms of the spatial relationships between artefacts and people, in particular the aspects of proximity and access that relate to components of the system, and a person's horizon of observation (what can be seen and heard from their point of view).

Each analysis level in this section starts with a diagram that is then described in progressively greater detail through summary, detail, further notes and issues.
The proposed structure is designed to enable the analyst to highlight potential design issues with the way the system currently works and is also meant to improve the analyst's understanding as he/she uses the model. These claims will be examined later in the thesis.

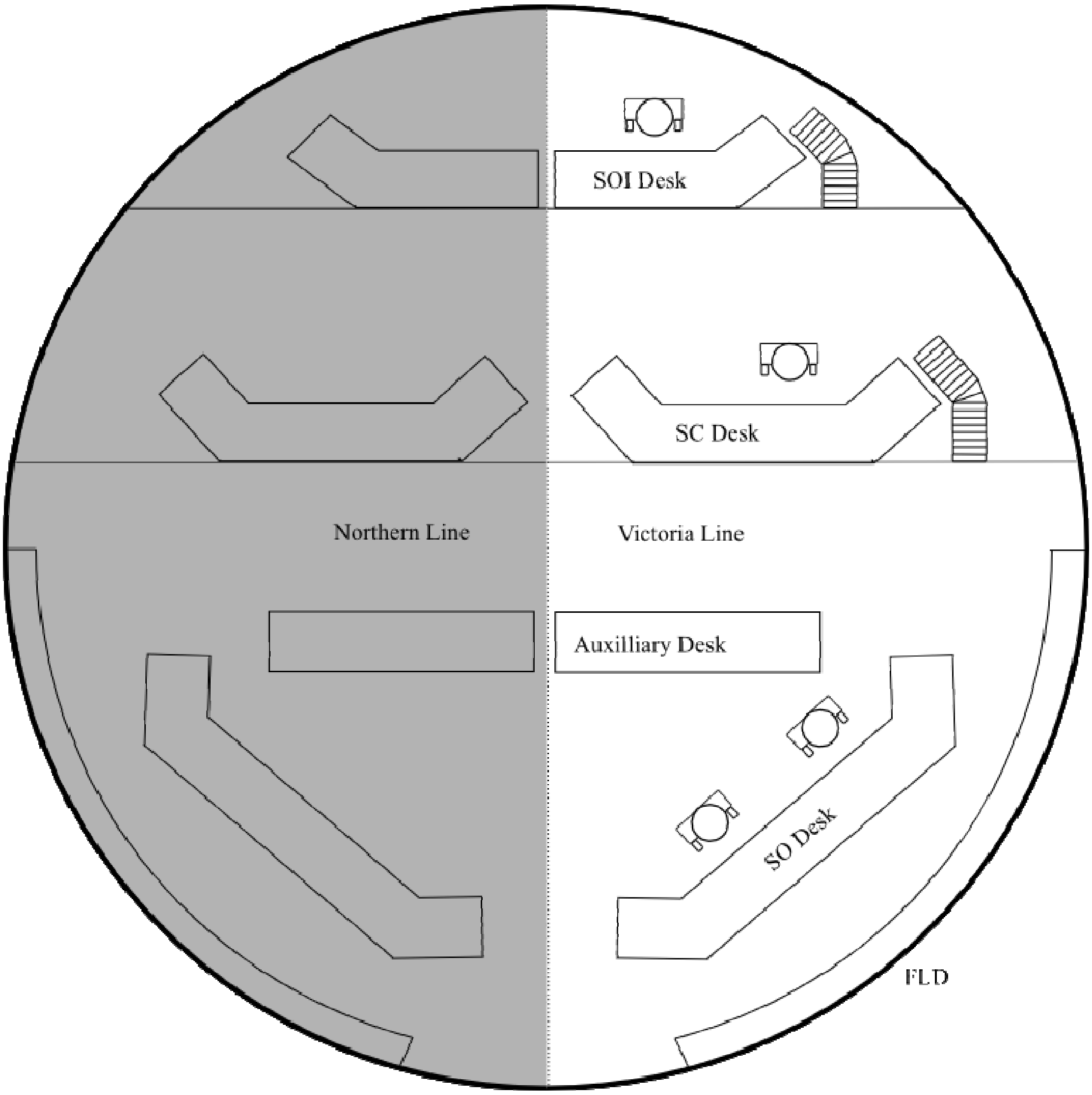
9.2.1 Room Level

SUMMARY

The control room at Cobourg Street is circular with one semi-circle dedicated to the Northern Line and one dedicated to the Victoria Line. For each line there are three desks, one for each role; SOI; SC; and SO. Each desk is on a different tier, the SOI desk being on the highest tier and the SO desk being on the lowest tier. All desks face the relevant fixed line diagram (FLD).

DETAIL

Figure 13: Control Room Layout



Communication (access to control room staff)
The SC desk is placed in the middle of the room on the middle tier to give a good horizon of observation thus reflecting the role's nature as decision hub. From this position the SC can clearly view what the SOs are doing and can communicate easily with them. From this position the SC can also if required hear what the SOI is doing and communicate verbally with him/her. It is not important for the SC to have a **view** of the SOI's work area. The relative positioning (i.e. SOI behind and higher) instead reflects the nature of the information flow between these two where the SOI needs to see what the SC is doing but the converse is not necessary. The SOs need to communicate directly with the SC but not the SOI. The relative distance between SOI and SO (with the SC between them) also inhibits unnecessary communication between these two roles.

All practitioners are physically positioned to be able to hear each other normally. This proximity with each other promotes shared awareness and strengthens the ability of the system to monitor events and transfer knowledge (i.e. staff learn from each other and as all practitioners are monitoring the relative position of trains, problems are less likely to be missed).

Access to artefacts
The artefact shared by all control room staff is the FLD. The three desks are arranged on different tiers so that everyone in the room can have an uninterrupted view of the FLD. The FLD extends for approximately one quarter of the circumference of the room and for most of the wall in this area. Clocks are positioned in several places along both FLDs so that they are accessible from many viewing positions. Despite its overall size much of the labelled detail on the FLD (e.g. station names and signal numbers) is small and not easily legible even by SOs who have the best view. Legibility is not served by the poor light in the room, particularly over the FLD. The lighting of the room does however help to highlight the red lights on the FLD that indicate train position. The legibility of the diagram does not appear to be a problem for any control room staff because they know where stations are from the shape of the line. SOs also know where signals are from the shape of the line.

FURTHER NOTES:

- The SOI and SC can see only those pieces of information on the FLD that are necessary to them; the position of trains and their relative position to each other (i.e. the gaps between trains); the numbers of trains expected by the programme-machines (illuminated as dot-matrix displays); the general shape of the diagram.
- When the SM enters the room to oversee operations, he/she will often stand just behind the SC to the SC's left in order to command a similar horizon of observation whilst also not obscuring the FLD for the SOI.
- All the chairs have swivel seats and casters to make access to the desk artefacts easier. This is particularly evident on the SO desk when it is manned by one SO.

ISSUES

- The room can be noisy. Occasionally the SC was observed to ask for hush when the noise was clearly just banter/laughter. This situation is exacerbated by the fact that the room is shared by Northern and Victoria lines (i.e. when one line requires intervention, the other may be stable). Despite the independence of control between the two lines, there are also some advantages gained by sharing the room (see section 9.4).

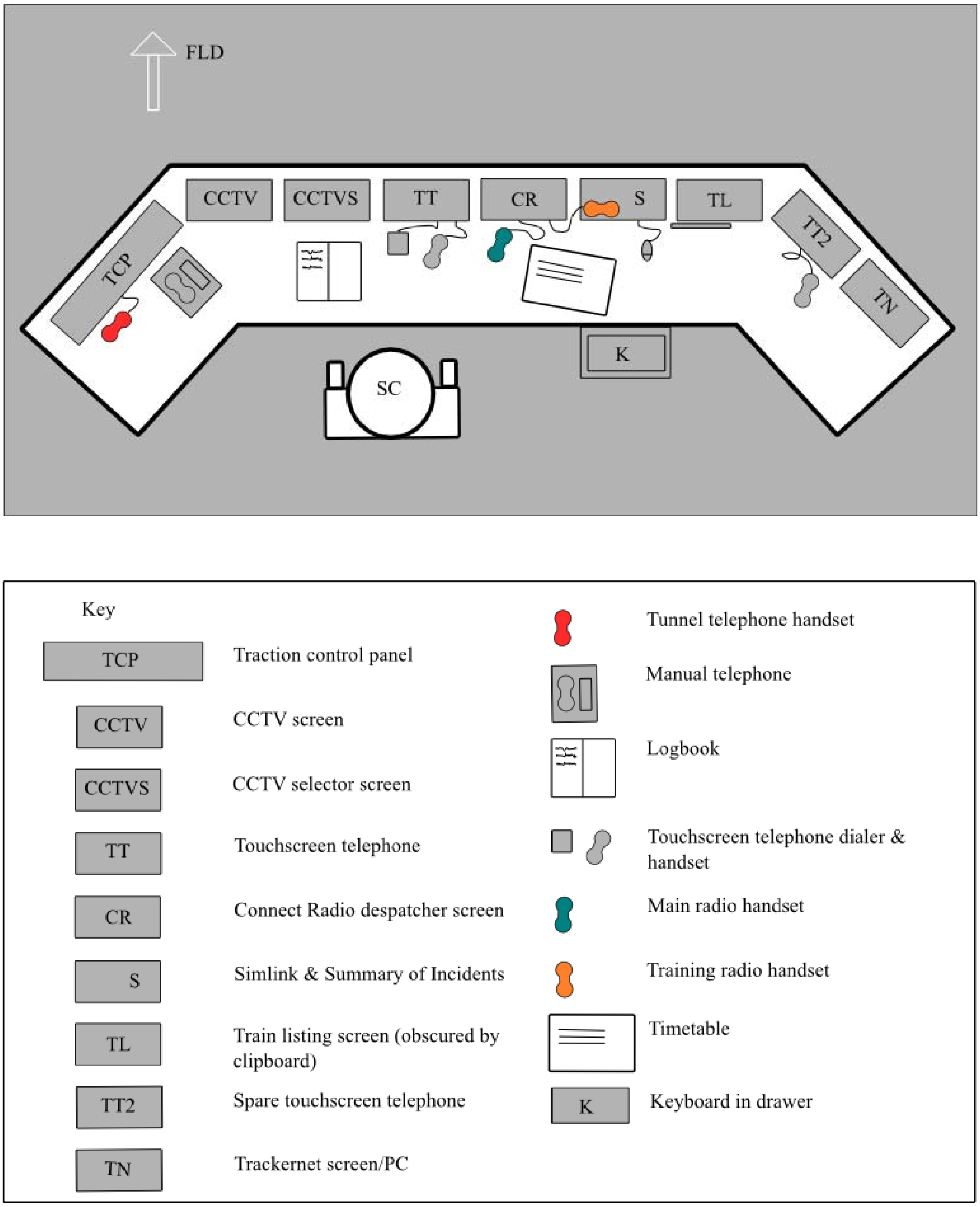
- All control room staff are skilled at listening out for those pieces of information that may be relevant to them – i.e. they "filter out" unnecessary noise.
- When it is noisy, the SC and SO may resort to communicating by phone. They often maintain eye-contact whilst on the phone to improve communication. This is helped by the angled position of the SO desk – SOs sit side-on rather than with their backs to the SC.
- The northern-most end of the FLD is partly obscured for the SOI.
- It was observed that when sitting down, the SC and the SOI may have difficulty seeing the tier below depending on their height. They often stand up to get a better view of the room below.
- The proposed structural change will result in more SCs all of whom must have greater access to the equivalent of the FLD than SCs currently have. The positioning of the SOI is of particular concern – where must he/she sit in order to overhear all relevant SC communications?

9.2.2 SC Desk Level

SUMMARY
The SC desk can be regarded as an information hub where the SC receives visual information from the stations via CCTV; information from external sources via the telephone and Connect Radio; information about the location of trains via the Connect Radio despatcher, train listing and TrackerNet screens; information about the state of other lines via the Simlink screen. This information must be integrated with other train location information provided by the FLD and in particular with the timetable in order for the SC to make the strategic decisions necessary to line control. The position of the equipment influences access to information and the way the SC achieves his/her task.

DETAIL

Figure 14: Layout of SC Desk



Access to artefacts

The equipment is arranged to best support **one SC** in performing line control whilst also allowing another SC to either help during handovers or to facilitate training. The most important pieces of equipment to have easy access to are the communications devices (telephone and radio) which are centrally positioned. There is a duplicate touchscreen phone for a second SC positioned to one side to avoid confusion. There is also a manual phone back-up should either of the touchscreens not be working. Less important equipment such as CCTV, TrackerNet and Simlink screens are positioned to either side of the main communications equipment. The traction current control panel is positioned on the far left to afford the best view of the old traction current wall diagram (which has never been used). Despite its importance the traction current control panel is rarely used and has a peripheral position to avoid accidental activation. Also, the fact that there is only one and it is positioned to one side of the desk reflects its safety-critical function and that only one SC should be responsible for it at any one time. Similarly to avoid confusion, there is only one timetable, one logbook and one copy of the traction current and signal diagrams book. Timetable and logbook are always kept centrally on the desk in front of the screens. The traction current and signal diagrams book resides on top of monitors for easy reference (see below). The incumbent SC will generally sit slightly to the left of centre and will use the mobile chair to reach other screens if necessary. The relief SC will during handover generally sit to the outgoing SC's right if the handover is particularly busy.

FURTHER NOTES

- The monitors are housed inside the recesses of the workbench and are positioned in a rough arc around the SC. The shelf on top of the monitors is used to store documents such as the traction current and signal diagrams book and the directory of radio and telephone numbers.
- The rarely used train listing screen is obscured (perhaps deliberately) by a clipboard.
- A trainee SC will generally sit left of centre with access to the main equipment while the trainer is positioned to the right with a good overview of the main screens and easy access to the duplicate phone and extra training handset for the radio.

ISSUES

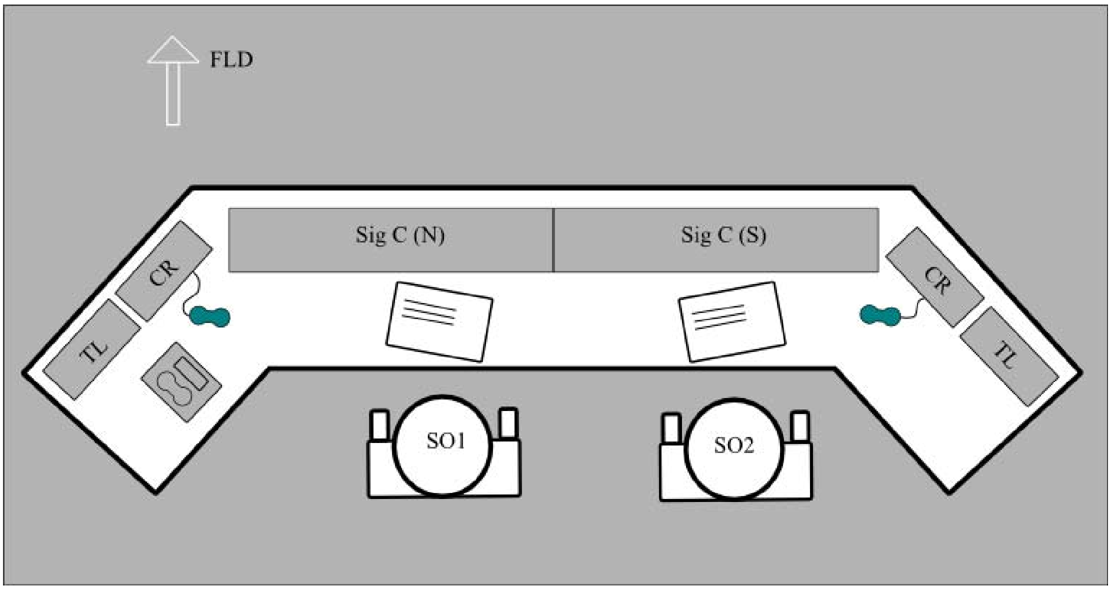
- The position of monitors is fixed and not under control of the SC.
- Perhaps the most important equipment the SC uses is the radio. The back-up radio is positioned on the auxiliary desk on a lower tier. A situation was observed when the main radio and the back-up radio were both found to be not working. This is a major problem because if a driver contacts the SC with a mayday, he/she cannot answer it. The problem was eventually fixed but the physical position of the back-up radio was an issue for the SC who suggested that it should be on the main SC desk (perhaps in place of the train listing monitor).
- If the intention is to physically relocate to the auxiliary desk in the event of equipment failure, this was not done. If it was done, the SOI would no longer be in close proximity with the SC making his/her job more difficult.
- The Summary of Incidents spreadsheet requires a keyboard for input. This is kept in a drawer housed in the desk to save space. SCs were observed to reach awkwardly for this when entering data whilst also keeping a central position on the desk, sometimes removing it from the shelf to get closer to the relevant screen. The mouse for the monitor sits on the desk and sometimes gets in the way when using the timetable, logbook or track and signal diagrams book. In general the use of mouse and keyboard for this one piece of equipment seemed

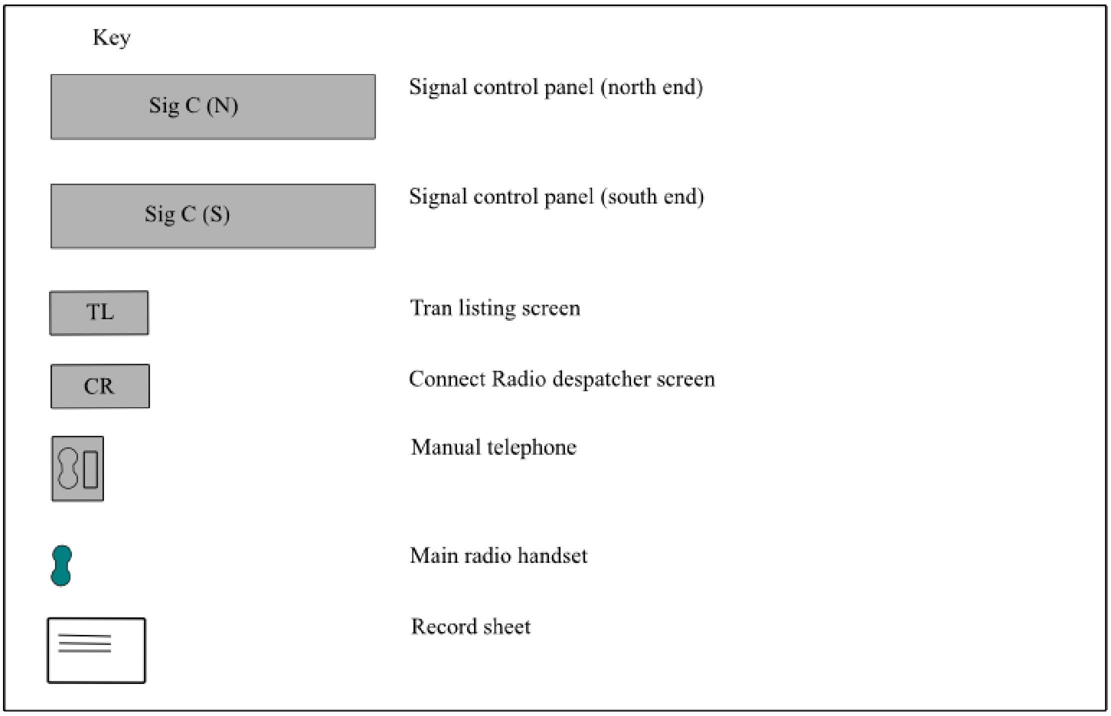
to cause some problems (e.g. lots of typos and frustrations caused by unwanted default data being entered in spreadsheet cells). SCs are accustomed to direct input (i.e. pressing real or virtual buttons as opposed to operating a mouse that required them to locate a secondary cursor on the screen).

9.2.3 SO Desk level

SUMMARY
The SO desk can also be regarded as an information hub where the SO receives information from external sources via the telephone and Connect radio; and information about the location of trains via the Connect radio despatcher and train listing screens. This information must be integrated with other train location information provided by the FLD and with the record sheets (that hold cut-down timetable information) in order for the SO to monitor the state of the line. The main control panel allows the SO to perform signal operations according to SC instructions. The position of the equipment influences access to information and the way the SC achieves his/her task.

Figure 15: SO Desk layout





Access to artefacts

The equipment is arranged to best support **two SOs** – one for the north end and one for the south end. It is possible for one SO to carry out line monitoring and signal operation duties. The most important equipment to have easy access to is the signal control panel. There are two control panels each of which is centrally positioned for each SO. Each control panel has a top half for selecting particular programme machines and a lower half for operating signals associated with a programme machine in manual “push-button” mode. Each SO has a train listing screen and Connect radio despatcher screen positioned at the end of the desk. The radios are configured to cover only the relevant half of the line (either north or south end). The train listing screens aren’t configured to reflect this partition but the displays are set to the relevant areas (i.e. all train listing screen information is available from either screen). Each SO has a manual telephone. Each SO has a separate set of paper record sheets relevant to either Seven Sisters (north end) or Victoria (south end).

FURTHER NOTES

- The control panel and monitors are fixed. The shelf on top of the control panel is used to store documents such as the directory of radio and telephone numbers.
- The control panel has many blank areas which are covered by paper notes as reminders for important and frequently used information (e.g. useful radio numbers).

ISSUES

- It was observed that a call made by a southbound TO to the north end SO which was dealt with and then cancelled off the despatch screen subsequently resurfaced on the south end radio as a new call. When the south end SO picked up the call, the TO was confused as he thought the SO had made the call. This is described by the SOs as a “software fault” but results from the way the radio was used to answer the original call. If the SO answers by making a group call, they will then have to physically remove the call request from their call stack. However, because a TO call request is initiated by a specified radio, the system is unable to recognise that the group call was in response to that, and so, regardless of the SO physically removing the call request notification, the system regards the original call request as unanswered. Thus, when the train enters a new area of control, the call request appears on the appropriate despatcher to that area.
- SOs pointed out that sometimes train numbers are slow to disappear from one area of the despatcher screen as the train moves to another area, causing duplicates to appear for a short while. SOs are particularly sensitive to looking out for duplicates which need to be resolved to maintain an accurate picture of train locations. The accuracy of the system (as manifested by the inexact nature of train locations on the despatcher screen) is expected to improve with the upgrade. Certainty of train location is important for the upgrade given the extra number of operators each responsible for a separate section of line and because the number and frequency of trains is expected to increase.
- The train listing screens are rarely used. SOs instead rely on the FLD, the radio screen and the cut-down versions of the timetable to pinpoint train location.

9.3 Artefact Model

Following Furniss & Blandford (2006), the analysis at this level concentrates on those artefacts and representations considered most important to the performance of the system.

For each artefact, the impact of its design on performance is considered in terms of how it influences either team or individual level cognition.

I have concentrated on the following three areas as being important for line control performance:

(i) The FLD (from SO point of view)
(ii) The Connect Radio despatcher screen (from SC point of view)
(iii) The timetable (from SC point of view)

SCs often refer to these three artefacts as being those essential for line control. The artefacts will either have slightly different representations or different uses depending on whether they are used by SC or SO. These choices of point of view are noted next to each artefact and reflect the focus most likely to be of use given the proposed organisational changes of the upgrade.

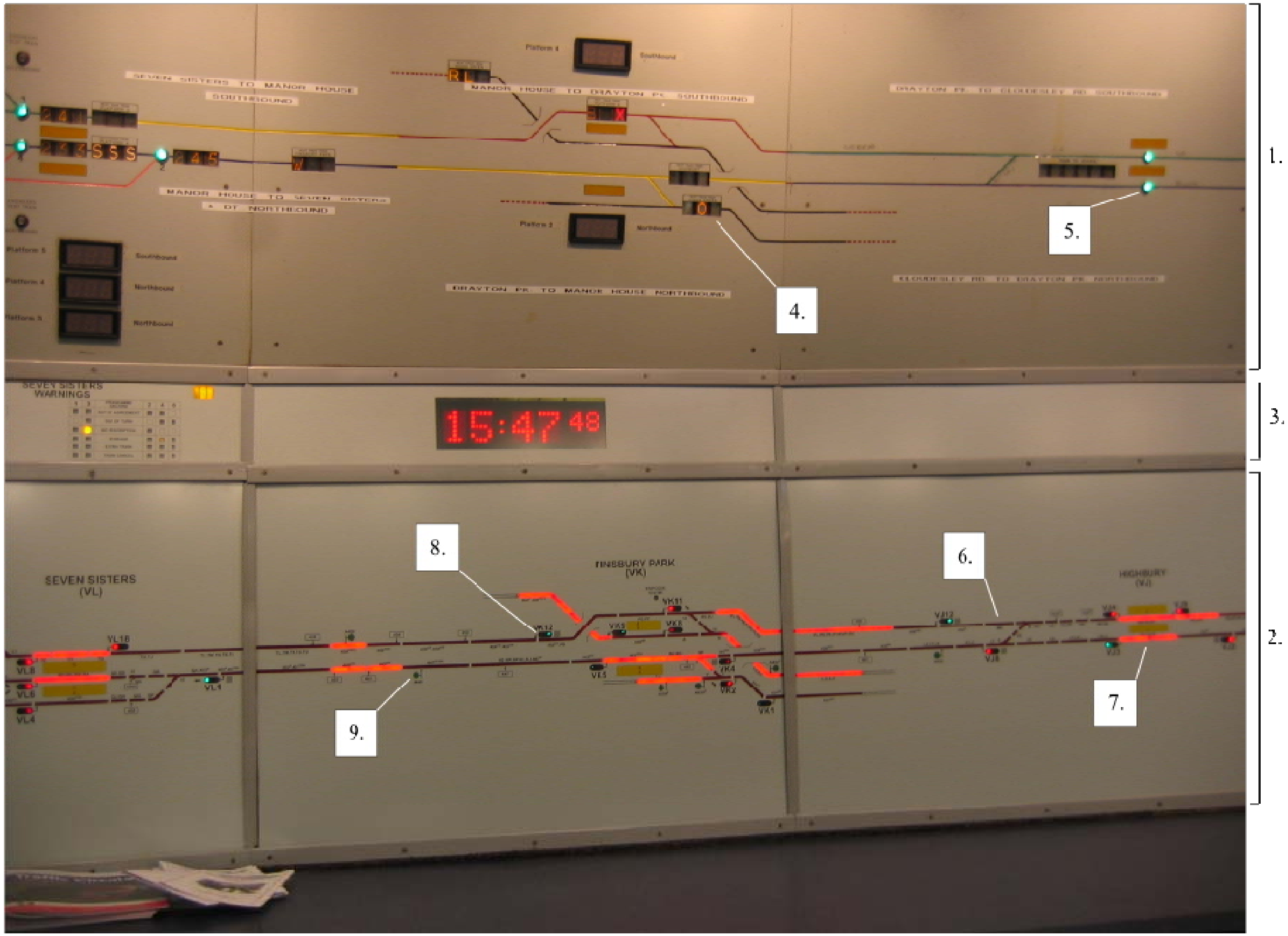
9.3.1 Fixed Line Diagram (FLD)

SUMMARY
The FLD is the most prominent shared artefact in the room and is used by all control room staff to help locate trains, to determine the state of signals and programme-control machines and to check the overall state of the service (i.e. is it busy, are delays imminent, is it stable and running to timetable?).

It represents a simplified map of the northbound and southbound tracks and stations. It is not to scale nor entirely accurate with respect to shape. For example, in some places on the actual line the northbound track crosses the southbound track. This detail is not shown on the FLD in order to remain consistent to the diagram convention that the northbound track is shown below the southbound track.

Figure 16: Fixed Line Diagram (see next page)

Figure 16: Fixed Line Diagram (FLD)



DETAIL

Fixed Line Diagram (FLD)

The FLD is split into an upper (labelled 1) and lower diagram (labelled 2) each of which is based on the same basic map of the tracks. Both diagrams are lined up so that the points linked by a vertical line connecting them relates to the same physical location. Upper and lower diagrams are separated by a middle bar (labelled 3) representing warnings at a location. The diagrams show points and cross-overs where trains can be reversed from one track to another. Both diagrams also show platforms in yellow, and the position of sidings and the depot.

1. The upper diagram shows the position of programme-control machines which control automatic signals. The tracks are colour-coded to show traction current information (although this is not relied upon for safety-critical decisions). Platforms are displayed but this information is not directly relevant to the use of this diagram. Individual stations are not marked although the station can be inferred by looking at the appropriate station labels for the lower diagram. Instead, sections of the track are labelled, e.g. “Seven Sisters to Manor House northbound”. Lights show the state of the programme-machine (see below). Three-digit dot-matrix displays (labelled 4) represent the train number the programme-machine is expecting according to the loaded timetable. Note: these are not actual train numbers and are never relied upon by control room staff to be so. Instead they may provide a clue to the location of a train if the service is running according to timetable.

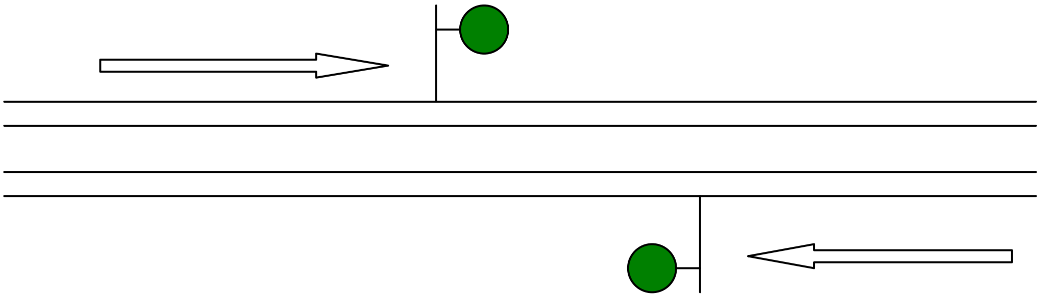
Programme-machines have the following states as denoted by the corresponding FLD light (labelled 5):

Light colour	Machine state
Red	“Push-button mode”. Machine is programmable, i.e. it won’t change from the current associated signal until the SO changes it.
Yellow	“First-come-first-served mode”. If there are two branches leading into one, the first train to reach the junction gets the signal.
Static green	“Programme-machine mode”. Except in the case of a warning, the machine controls the signal according to the train number, time and destination information loaded. In this mode the warning bar (labelled 3) is operational. This bar shows a list of warnings the system is designed to detect, e.g. an “out of agreement” warning means the train description does not match what the timetable is expecting. When the warning is detected, the appropriate light on a list of warnings lights up and an audible warning is also given. In this situation the SO has one minute to react. If he does nothing, the machine will route the train according to the loaded timetable.
Flashing green	“Programme-machine-only mode”. The warning bar is not operational. The machine controls the signal.

2. The lower diagram shows the position of individual signals and **gives an indication of** the position trains. The tracks are represented by slightly separated red lights, each light denotes one piece of track (labelled 6). An illuminated light (labelled 7) represents the fact that something (usually but not always a train) is on that piece of track.

The station labels denote sections of track with an associated code that prefixes all signals in that area (e.g. VK = Finsbury Park, VL = Seven Sisters). Each signal is labelled with a prefix code and a number (e.g. VK11). Automatic signals that the SO can manipulate if required are shown by a light (labelled 8) that represents signal state (green for "go", red for "stop"). Signals that the SO cannot manipulate are shown by a green painted dot (labelled 9). The orientation of signal symbols also denote the direction of trains.

Figure 17: FLD signal symbols



Each SO control panel has a top half for selecting particular programme machines and a lower half for choosing signal operations for a programme machine in push-button mode. The lower half also allows the SO to enter data (e.g. train number) into a programme machine.

Applying Resources Model to FLD

Following Distributed Cognition principle 9 that refers to the coordination of resources as described by Wright et al. (2000) in their Resources Model, use of the FLD can now be examined. The Resources Model identifies six abstract information structures that can be described independently of the representation inherent in an artefact. The abstract information structures are: plans, goals, possibilities, history, action-effect relations and states. Before information can become a resource for action, it must have a representation, one that is either external (i.e. in the interface), internal (i.e. in the user's head), or distributed both internally and externally. The SO treats the FLD as containing a set of external resources which he/she can coordinate with other external and internal resources in order to assist in the activity of monitoring/operating the line.

For example, if northbound trains are to be turned onto the southbound track early at Seven Sisters, the relevant section of the FLD is identified on upper and lower diagrams (by track shape and horizontal location on the wall rather than labels). This localised portion of track diagram with its associated programme-machines and signals constitute a set of structural possibilities or affordances. A stream of northbound trains arriving at this localised portion of track constitutes a list of goals (i.e. a set of trains that must be re-routed). This list of goals, although ordered, is not a plan because it doesn't contain the actions necessary for trains to be re-routed. The plan, i.e. the sequence of actions that must be carried out to achieve the goals, is not external but internal. The SO must formulate a plan based on what must be done and what is possible but this plan has no external representation in the artefacts at his/her disposal. An interaction history, differs from a plan (that it is also a sequence of actions) in that since the actions are in the past, the history cannot by definition contain any branching or looping. SOs keep their place in the plan by recording a history of train movements in the record sheets. Action-effect relations (i.e. causal relations between actions and system states) exist in manuals and rule books but in practice they have become entirely internalised as SO knowledge. The FLD represents states externally although these states require interpretation and are associated with a reliability that comes from internal SO judgement. For example, a discrepancy between the train number indicated by the programme-machine number displayed in the upper diagram and the information displayed by the despatcher screen indicates an uncertain state that must be actively resolved through comparison with other external representations.

The external coordination of these information structures relieves the SO from having to internally coordinate this complex activity. Separating the diagrams into upper and lower halves provides a physical means of easily attending to the right information at the right time, and avoids the diagram becoming too cluttered. When for example a special service is being run, the numbers displayed on the upper diagram are meaningless. The SO can therefore concentrate exclusively on the lower diagram safe in the knowledge that he will not rely on erroneous train numbers by mistake.

The second part if the Resources Model deals with interaction strategies, i.e. how resources inform action. In the above example, the SO appears to be adopting a plan-following strategy, i.e. coordinating a pre-formulated plan with a history of actions. He/she may be monitoring the plan closely for anomalies (e.g. trains that arrive out of turn and which may need re-ordering) and in this case the action requires a measure of plan construction (i.e. reducing the difference between current state and goal state by selecting from possibilities to formulate an altered plan). By contrast, the different interaction strategies adopted by the SC reflect his/her role as a strategic decision maker. Here, the SC may have taken the decision to reverse trains early as a response to some perceived problem with the service as a whole. The SC's decision may be seen as a form of plan construction where the goal is defined as a "normal service". Train reversal changes the state of the service as represented by the FLD and other external representations and therefore may result in a new plan being formulated "on the fly".

FURTHER NOTES

Control room staff are acutely aware of the source of the information that is represented on the FLD. They know for example that the track lights on the lower diagram don't necessarily represent trains, just an object on the track. They use this source knowledge together with knowledge of the patterns of light changing over time to derive a sense of what the FLD truly shows. For example, perhaps a series of uninterrupted lights shows a set of bunched together static trains (and therefore a potential delay) or a problem with the section of track (which may or may not also be holding one or more trains).

ISSUES

- It is crucial that staff understand the source of information displayed on any replacement to the FLD in order to attach an estimate of its reliability and to diagnose what deviant patterns of information might mean.
- SOs are highly practised at coordinating resources of the control panel, the timetable, radio screen and FLD in order to operate and monitor the line, however the upgrade represents an opportunity to improve the mapping between control and displays to

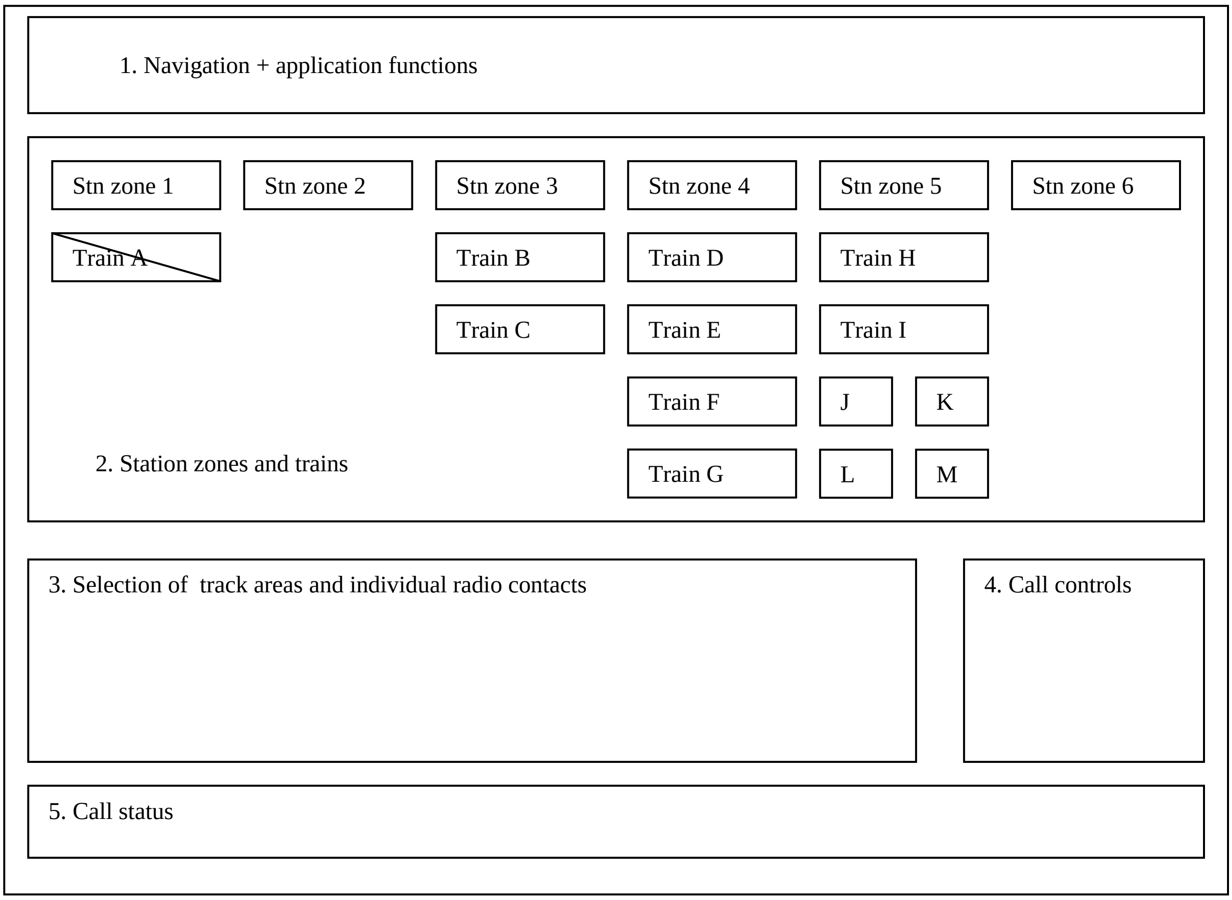
make implementing train moves easier to perform and learn. There is considerable physical distance between existing displays and controls. An interface that combined displays and controls into one would make the mapping more direct. Care must be taken not to clutter these interfaces – perhaps automatically only showing the information necessary to the current context (e.g. if a special service is running, hide the programme-machine numbers). Also a duplicate version of the information should be visible by other control room staff.

- Allowing staff to tag trains on the FLD with what they believe to be the train number may save them from having to remember and closely plot individual trains. It could however be argued that the lack of train numbers forces staff to build and maintain their own "picture" of where trains are and that this system is useful in highlighting errors. Positive Train Identification (PTI) on the Northern Line displays train numbers on the upper diagram at programme-machine locations next to the timetabled numbers the machine is expecting. The placement of PTI numbers like this reflects (and advertises) the uncertainty and transient nature of the information, i.e. it says, "This train was recorded as passing through this section of track". It does not say, "Follow the progress of this train along the entire track length – wherever the train moves, it will always be this number." Tagging trains with staff expectations of ID may lead to dangerous reliance on the reliability of that information.
- The above discussion regarding the potentially different interaction strategies adopted by SC and SO **during the same incident** indicates that the FLD (and other artefacts) are used in different ways to achieve different (although compatible) goals. The goals of the SO can be regarded as sub-goals of the SC. Since the roles are to be merged in the proposed upgrade, the challenge remains to design an artefact to replace the FLD that currently caters for the different SO and SC goals and interaction strategies.

9.3.2 Connect Radio Despatcher screen

SUMMARY
Due to the SC's role in the system as decision-hub the Connect radio despatcher is a central artefact facilitating much of the communication with actors external to the control room. The layout of the screen heavily influences the way the SC conducts activity, and therefore the performance of the system, by structuring the work and shaping the way this external representation is coordinated with other representations.

DETAIL
Figure 18: Connect radio despatcher – Mimic screen



The SC will generally keep the mimic screen as the default screen on the device.

1. The top part of the screen contains navigation buttons to other parts of the application e.g. tools, functions related specifically to group calls, functions for making text messages etc. (For upgrade rolling stock a function to enable PA announcements to trains will also be available.)
2. The central part of the screen displays up to six station zones at a time arranged as columns, labelled with abbreviations denoting particular stations (e.g. "SVS" = Seven Sisters). The station zones are ordered geographically from left to right north to south (following the convention of the FLD). These zone labels are disabled functions (i.e.

registered through the use of greyed out text) which for an SOI's radio would be enabled to allow them to contact staff at stations. Within each column is a list of trains currently located in that zone. Interestingly, there is no representation of which direction the trains are travelling (northbound or southbound). Each train representation is a button allowing contact to be made with the TO. Buttons are generally labelled with two numbers: the four-digit car number the TO is occupying and the three-digit train number. In this configuration, the car number is larger and more central than the train number although the display can be altered to just show train number. A train representation with a diagonal line through it denotes that the driver has his cab radio switched off (i.e. contact is diverted to the driver's handheld radio for 30 minutes). The order top to bottom indicates the order in which these trains entered the station zone. When there are more than four trains in a zone, the representations reduce in size to allow more to fit on the screen. Train movements can be tracked by watching train representations disappear from one station zone and appear in an adjacent zone, and from this the train direction can be inferred.

3. This part of the screen enables the SC to change the zones displayed e.g. a button labelled "KSX – GPK" displays the station zones from King's Cross to Green Park. Other buttons allow the user to reach parts of the system where individual calls to other contacts can be made.
4. There are five call controls: Silence (silence the ringtone associated with an incoming call), End call, Group, 1-to-1 (private call), and PTT (Press To Talk) buttons.
5. The bottom strip is reserved for call status information, for example, the default group which can be contacted just by pressing the PTT.

The SC's goal in interacting with the radio is to receive information from outside the control room regarding the service, and then having formulated a response, to either send instructions or request further information via the radio. In practice, the SC generally makes more calls via the radio than he/she receives. This is because once a problem has been reported or identified, there are a number of contacts that might be contacted. The SC may make a plan internally about which contacts to call and in which order – this is not represented externally in the system. A guideline of who to call and in what order in a certain type of incident is taught to the SC who internalises it and may modify it "on the fly" depending on the unfolding specifics of the problem. The goal: "all relevant contacts called in line with resolution of an incident", again is not externally represented. The radio mimic screen does present a number of communication possibilities: trains and stations that are located in the affected area. The stations are not directly contactable from the SC's mimic screen but the representation does still show them and the rough geographical relationships between them. One of the reasons the mimic screen is kept as default is because it presents these possibilities. The range of potential actions displayed on the mimic screen also represents **some** possibilities regarding the type and nature of communications, e.g. 1-to-1 or group calls. However, the complex configurations of calls such as combining communications to a station, technician and driver can only be achieved from setting up a patch on a different screen. Setting this up entails temporarily losing sight of the mimic screen with its representation of trains moving between stations.

The history of which communications have been made (and therefore where the SC is in the plan) is externally recorded in the logbook. A history of call-back requests can be saved via the radio and this can help the SC to make further calls to the same contact without the need to find it again, but this external representation suffers from a number of problems: it needs to be actively maintained on a different radio screen; the history doesn't record anything about the content of the call (whereas the logbook can); the history doesn't distinguish between separate incidents, i.e. calls are recorded in the order they are made and received, whereas the logbook can semantically group sets of calls if required. Action-effect relations are represented externally in the interface as changes to what commands are available following each interaction. States relating to calls are externalised as statuses: "ringing", "connected", "failed", "busy" etc. The changing location state of trains is also externally represented, although track direction has to be inferred by monitoring this over time. Interaction strategy can be characterised as a combination of plan-following (i.e. an initial precomputed plan) and plan-construction (reducing the difference between current and goal states in response to changing situation, e.g. a technician may find a problem with a slow-running train that requires it to be taken out of service, entailing new communications to be made by the SC).

ISSUES

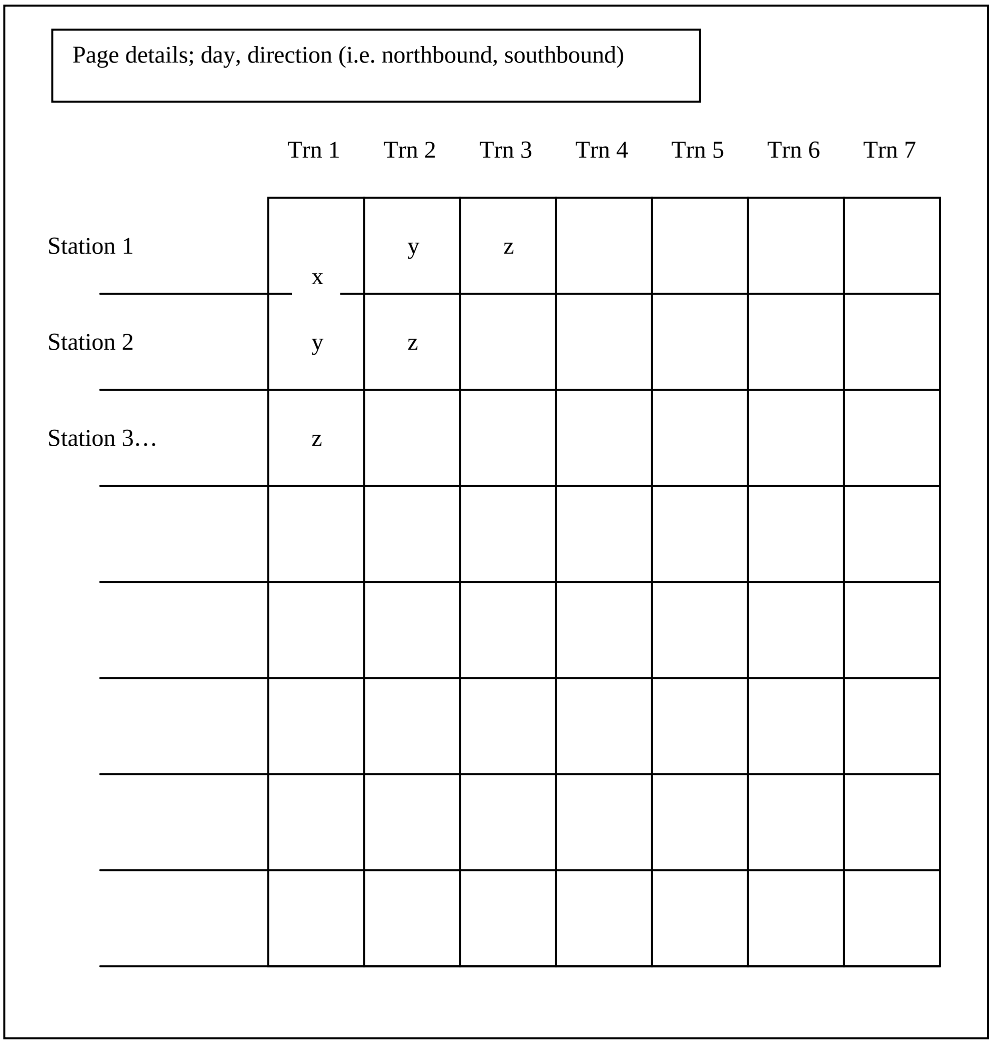
- Given how important the mimic screen is to the SC as a source of train location, this information should be available from during all interactions with the radio during an incident. Interestingly, the screen was never designed to function in this way. However, SCs adapted to using it as a further clue to train location in the absence of more reliable information. Originally, the default screen was envisaged to be the call-stack screen.
- Train location information may be improved by showing the movement of trains in a similar way to the FLD (i.e. track direction and with more detailed train position)
- The performance of the SC may benefit from the support of external representations of plans and histories.
- The proposed upgrade structure entails two Level 2 SCs each responsible for radio communications associated with up to seven different physical sections of the line. Problem trains may still be mobile and move into another SC's area of jurisdiction – the system must take this into account. For example, will a handover of trains be necessary as they move from one area to another? What will happen if this occurs while a communication is being made? Will one SC be responsible for the communications of a particular incident? If so how will that responsibility be assigned?

9.3.3 Timetable

SUMMARY
The timetable has a number of different functions for the SC: it helps in the location of trains; it shows opportunities for the changing of the service; it can be annotated to record history; and it assists in determining the overall state of the line. The timetable represents an ideal service and the information it contains is replicated in the information loaded into programme machines that control the signals.

DETAIL

Figure 19: Timetable page



The timetable page is a grid with individual trains represented as columns, the stations on their routes as rows and times of departure (and occasionally platform number) shown in the cells at the intersection. The column headings show train information: running train number; trip number; and crew number. Note also that time increases both vertically and horizontally in the grid and that diagonals (in the bottom left to top right direction) roughly show constant time. SCs are highly practised at exploiting the timetable structure to find information. For example, if the service appears to be running normally (i.e. to timetable), the presence of a train at a station on the FLD will be combined with the time as given by the 24-hour clock on the FLD. Time and station will be coordinated with the timetable to find a train number. Thus the SC will be reasonably confident of the ID of the train represented on the FLD (and by implication of the trains immediately south and north of this train). By following the diagonals of constant time, an SC can see where all the trains on the line are meant to be at any point in time.

The timetable pages are covered in transparent plastic to allow the SC to annotate the information with an erasable chinagraph pencil. Vertical lines through columns indicate, for example, that a train is cancelled. Arrows denote a different order of trains and vertical lines with a horizontal base indicate that the train is to be sent to the depot. These marks coordinated with timetable information function as an external history – helping the SC to keep track of changes.

More permanent annotations are made to the actual timetable pages to highlight opportunities for SC service moves which assist in planning. Specifically, red rings are drawn around trains where the TO is due to change (because of a shift end or break). These are seen as opportunities to reform the service because a change to the number of the train has implications for the existing TO's shift and so using these "pick-up" trains simplifies matters. The following example illustrates the use of the timetable for reforming the service.

N/B trains	232 *	244 *	236	237	233 *
Timetable	14:00	14:03	14:06	14:09	14:12
Mins late	3	7	3	On time	9
Relief TO	A	B			C

(* = pick-up train)

There are three pick-up trains, so three TOs waiting to relieve their colleagues – A, B and C. 232 will arrive first but to get the service back to timetable, TO B will take it instead and make it into 244 (244 is now on time). That means that the 244 that hasn't arrived yet must be changed to avoid duplicates. By making it into the 233 and getting TO C to take it after a two-minute wait at the platform, 233 is on time now too. The 233 that's still on the track yet to arrive for another 9 minutes will be given to TO A and made into the 232. Now there are no duplicate train numbers on the system but the newly formed 232 is now 21 minutes late so it's reversed early onto the southbound line. The 236 is still 3 minutes late but the service is much more to timetable. The SCs visualise (and note these reforming moves in exercises and in the logbook) in the following way. The structure of the notation is similar to that used in double-entry bookkeeping and helps to ensure that duplicates won't result from service reforming.

232 X 244
244 X 233
233 X 232

A spare TO waiting on the platform could be used by the SC in the reforming moves to ensure 236 runs on time too:

232 X 244
244 X 236
236 X 233
233 X 232

In the example, the SC uses the timetable as an externalised goal (i.e. a representation of the ideal service). The red ring annotations are possibilities and the logbook entries show both a history of moves and an externalisation of action-effect relations (i.e. changing train numbers affects existing trains and implies further necessary changes until the duplicates are resolved). The individual steps and branches of the plan are still internal to the SC. The interaction strategy is one of plan-following.

ISSUES

- Since SC and SO roles are to be merged as part of the proposed upgrade, the external representations of trains could be highlighted to show reforming opportunities (as the timetable currently does now). The resulting system could capture a history of moves and also provide some validation to the SC to highlight duplicates that may arise as the result of reforming moves.
- The only artefact that represents the number of minutes a train differs from the timetable is the train listings screen. Such a representation is analogous to the flight director interface that indicates to the pilot which direction to steer to maintain a desired flight path (Wright, Field & Harrison, 2000), but may be more useful to a SC if it is coordinated with the type of train location representation currently shown by the FLD.

9.4 The Development of Practitioners Model

SUMMARY

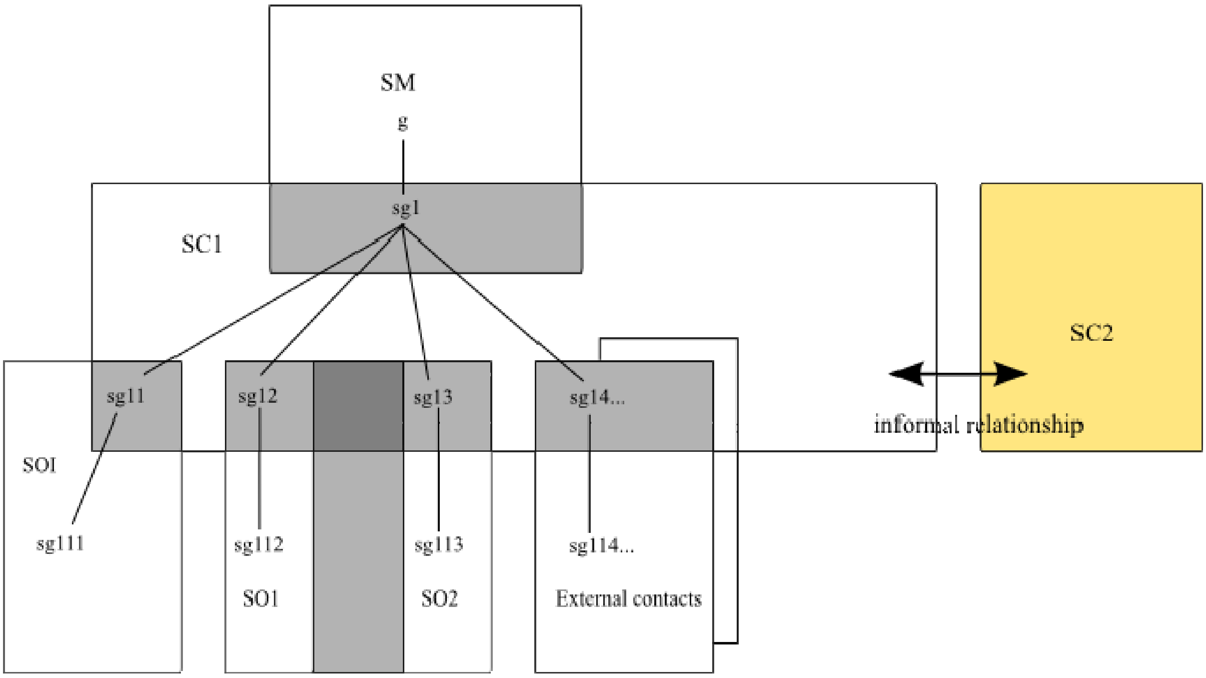
The development of practitioners here is concerned with how the system learns through the developing knowledge of the control room staff. This knowledge is accumulated over the span of practitioners' careers and is partly a function of the way work is socially organised, i.e. through the relationships between roles in the system. The analysis starts with a high-level summary and a diagram that represents the current social organisation of the work. The relationships between roles are then described in greater detail taking into account the ways in which the different roles are recruited and are likely to progress over the course of a career, i.e. how does the previous experience of control room staff influence the knowledge they contribute to the developing system?

This level of the analysis concentrates mainly on giving a snapshot view of the way the current activity of line control is socially organised in terms of the relationships that exist between key practitioners. What is important here is the way in which the practitioners relate to each other rather than the information flows between them. Hutchins (1995) describes the way in which a hierarchical structure can map to a goal structure such that areas of assigned responsibility overlap between superordinate and subordinate ensuring that sub-goals of the overall goal are satisfied. This organisational structure not only influences the way in which work and responsibility is shared out but shapes the way knowledge is learned and retained in the system.

In line control a hierarchical structure exists although at least within the control room the nature of it is less rigid and clearly defined than in the military setting Hutchins describes. The SOI and SOs instead actively support the SC rather than receiving orders. In particular, the SOs may offer advice and negotiate with the SC to arrive at a solution.

The data in this section of the analysis comes from observations and interviews with control room practitioners. Some insights were taken from a recorded interview conducted with two senior London Underground employees both of whom have had extensive experience involving different roles and different lines.

Figure 20: Social organisation of line control (adapted from Hutchins (1995) pp203)



The diagram shows the areas of overlapping responsibility inherent in the hierarchical structure of key roles in the activity of line control. The goal structure g, sg1, sg2 etc is superimposed to show how the work is shared amongst key personnel and how the sub-goals that contribute to the overall goal can be met independently between levels (e.g. sg111 is accomplished independently of the SM and outside his immediate area of responsibility). SC2 represents the service controller for the Northern Line whose relationships are similar to those of SC1 but are not shown for reasons of simplicity. There are many external contacts that have a relationship with the SC, e.g. DMT, TO, station supervisor etc. For the purposes of this section not all the individual relationships between different external contacts are explicitly described, rather the common nature of these relationships is examined.

In addition to a description of the pool of career knowledge in the control room, the following key social relationships are described: SM-SC1, SC1-SO, SC1-external, SC1-SC2.

The pool of career knowledge: how practitioners develop

Before the 1990s all promotion within London Underground was conducted on the basis of seniority. Competence was checked through exam performance but the key to promotion opportunities was length of service. There were only four jobs in operations that were outside of this regime: line controller, area manager, railway instructor and trains inspector. This system ensured that career progression was slow but it also resulted in the build-up of a pool of knowledge for practitioners to draw upon during the activity of line control.

A good example of the system of seniority applies to the SO's role described by one SO as "dead man's shoes" in that a candidate would have to wait for positions to become free following death or retirement. Originally known as signal controllers these practitioners had to come from a signalman background. Typically they served an apprenticeship in a signal cabin starting from the age of 15. By 20 they might make signalman, cabin man at 25, then relief signalman who could operate different signal cabins. The role of SO differs from a remotely based signalman in many respects, for example the increased complexity and responsibility that comes from operating the entire line with a manager overseeing performance. However, the years of knowledge gained from working at remote signal cabins is valuable to the SOs in understanding how the technology works out in the field.

Line controllers did not have to fulfil this career requirement and could come from any background. Originally TOs were likely candidates for the role. Certainly before the advent of radio, the TO had to be a proactive problem-solver since often he could not rely on the controller for assistance. The role of TO has changed considerably with the evolution of technology and on the Victoria Line his task is largely automated. More recently, a lack of suitable candidates for the role from within London Underground resulted in SCs being recruited from military or police backgrounds since it's thought that these candidates possess the structured thinking and effective decision-making skills necessary for dealing with incidents, especially safety-critical ones. There are set procedures for dealing with certain types of incident and those with a military/police background are thought to be good at applying these procedures under pressure. Not all trainees make it to become SCs – some otherwise bright candidates may "freeze" under complex realistic conditions.

Generally, previous experience from within London Underground is highly valued, for example, SOIs are often ex-TOs. Some SCs have extensive experience of many roles: SO, station supervisor, TO etc. It is unlikely however that once practitioners have reached the control room that they will change roles due to a lack of incentive. This is because the pay structure of SC, SO and SOI roles do not vary considerably. This is in contrast to the military setting described by Hutchins (1995) where knowledge is accumulated through career progression: as each successive position is learned, the knowledge gained is useful to the next position. In order to compensate for the relative lack of career movement within the control room, knowledge is actively shared (both formally and informally) so that each role understands the expected responsibility and tasks of other roles (see Relationship: SC1-SO below). People are also acutely aware of others' backgrounds and so they know who to ask or rely on if the activity requires knowledge outside of their personal expertise.

ISSUES

The change in recruitment policy away from the basis of seniority is driven not just by the need to allow quicker career progression, but also by the evolution of technology. For example, the replacement of remotely stationed signalmen by programme machines ends the signallers' apprenticeship system and means that the pool of SO-related knowledge will no longer be built up from experience of this kind. Of course, practitioners with SO backgrounds and experience as signallers will remain in the control room for some time into the future. However, this projected loss of knowledge (whether it is important or not) may be accelerated by the proposed merging of SC and SO roles simply because Level 2 SCs will implement their own signalling moves, and so the opportunity for sharing such knowledge will diminish.

It is also likely that if the newly merged role is to be recruited from experienced SCs and SOs, the training required by practitioners from these different backgrounds will be different.

Relationship: SM-SC1

The SM has overall responsibility for the smooth running of the service and is concerned primarily with reducing delays, in particular those delays that are attributable to staff under his control. The SM is the senior operational manager on shift for the whole line and has the final say for all issues affecting trains, signals and stations. A system of abatements exists between London Underground Ltd and the infrastructure company MetroNet that owns and maintains the rolling stock and the track, whereby penalties are paid to each other for failures of service depending on where the responsibility lies. The SM's major priority therefore is to both keep track of delays and reduce delays from the overall perspective of running cost. The SC, on the other hand, is concerned with making **safe** operational decisions that result in as few delays as possible. In other words, the SC's major concerns are safety and keeping the service as close to timetable as possible, but he/she is not directly concerned with the financial cost of disruptions. The SC has freedom to deploy the resources at his/her disposal in any manner he/she chooses but may be held to account about the actual decisions taken. The SM occasionally leaves the managers' office to observe activity in the control room especially during a major incident, and may take executive decisions (see below) but rarely interferes with operational decisions.

Tension may develop due to incompatibility between the subtly different goals of the SM and the SC. For example, an incident occurred where a broken rail resulted in a speed restriction being imposed for this section of track. A high-level strategic decision was made to close the track section rather than operate a hampered service. This decision was taken during the previous shift but was not recorded in the SC's logbook and is therefore likely to have been made by the SM. The SC who inherited the incident at the start of his shift explained that in order to stabilise the service he instigated a special service but took out fewer trains than he calculated he would need to minimise disruption. He did this because it would be politically unacceptable to management to take out more trains. The resulting service was a number of minutes late as he predicted, but this provided him with the justification he needed to further reform the service.

Tension may also develop where the SC task of informing the SM of developments to the service conflicts with the task of responding to incidents. However, the relationship generally exists without tension because of the mutual respect that arises from the fact that the SM is likely to have experience of service control and because the boundaries of responsibility are clearly understood by both parties.

ISSUES

The proposed organisational changes of the upgrade require a certain amount of high level strategic decision-making to be transferred from the SC to the SM. Confusion may arise if the new boundaries of responsibility between them are not clear.

It is also possible that the shift in activity between the two roles may result in the SM making decisions that are now his/her responsibility in a different way to how the SC would have made them because their respective overall goals remain different.

There is an issue regarding whether the new strategic operational decisions the SM must make may suffer if he/she is to remain located mostly away from the control room.

Relationship: SC1-SO

The responsibility of the SO is to implement the strategic decisions made by the SC although, as has already been explained, the sharing of these responsibilities and tasks is not clear-cut and depending on the relative experience of the two people, the SO will suggest moves that alter the service as well as implementing them. If the service is not particularly busy, the decision process may involve some negotiation. Despite these blurred boundaries, the overall responsibility for maintaining a stable service without delays and making virtually all safety-critical decisions remains with the SC. The SO's work contains a safety-critical element in that he/she may give instructions to a TO. The SO is free from concerns about delays (although he/she is acutely aware of the responsibilities of the SC) and if there's a choice about how the move can be implemented will take responsibility for these detailed decisions.

ISSUES

The proposed merging of SO and SC roles will end this relationship. Possible consequences include the loss in transfer of knowledge between the two – a crucial means the system has of learning the changing practice of line control.

Relationship: SC1-external

Although the relationships within the control room are not overtly hierarchical (except perhaps during a busy incident), the hierarchical relationship between the SC and external contacts is generally explicit. One senior SC was observed to reprimand a trainee about the manner of her communications over the radio to a TO: "You don't ask them if it's all right to do something. You're the controller – you tell them what to do." This style of verbal communications is about engendering the right tone crucial to safety-critical situations rather than pulling rank.

One exception to the clear hierarchical relationship between SC and external contacts is SC-DMT. Their relationship with respect to line control decisions can be described as collaborative. However, technically, DMTs are a higher grade than SCs (a fact that irritates experienced SCs), and experienced SCs generally earn more money than DMTS (a fact that irritates DMTs). This tension between the two roles may cause the relationship to suffer.

The SC must develop a set way of speaking over the phone/radio, in particular adopting certain protocols to make the communication clear, but also judging the confidence of responses from the external contact. The SC can pick up different clues about this, in particular whether the external contact is also adopting the correct protocol. For example, if the SC is asking a station supervisor to pull out switches to remove power from a localised section of track, he/she will first take off traction current for the circuit the track section is contained within so that the supervisor can safely touch the switches which are numbered e.g. 1001 and 1001a ("1-0-0-1 alpha.") The SC's task is to make sure that the supervisor has pulled out the right switches and that both have been removed properly before switching the traction current back on. If the job has been done correctly, the localised track section will be without power at this point. If the supervisor only pulls one of the switches out and the traction current is then switched on, this specific section of track will become live. The SC has to obtain confirmation via the correct protocol or any resulting casualty will be his/her responsibility – evidence is supplied from the recorded conversation. If, for example, the supervisor's response is, "Yep, done that, guv," the SC will repeat a request for confirmation explicitly asking for who is speaking, where they are and what their message is. The identity of the external contact is important because in this situation the protocol requires a "responsible person", i.e. the named individual who has requested that traction current be taken off. Insistence on precise language is also vital for the SC to ensure that instructions have been carried out correctly. If, for example, a supervisor is physically securing a set of points to normal and says, "I've secured those points *normally*," the SC will respond, "No, supervisor. Positions are normal or reverse. Please confirm the position of the points. Do you understand, over?" SCs must also be vigilant as to the demeanour of the external contact. If the contact is panicking, for example, then the SC will place a lower confidence in what has been said and may request for action to be checked and reconfirmed by someone else. External contacts can be requested to carry out some action but they cannot be ordered, i.e. they have the right to refuse if they do not feel comfortable with the situation, therefore the SC's own demeanour is also important. It is therefore vital that the SC should put the contact at ease in advance of safety-critical instructions and he/she cannot afford to lose his/her temper whilst in communication.

ISSUES

External contacts are accustomed to dealing with one SC who is responsible for the line. The proposed merging of SO and SC roles implies that more than one practitioner will take responsibility of different sections of the line, a situation that may require adjustment of the relationship between SC and external contacts.

Relationship: SC1-SC2

Practitioners are trained to be able to perform their roles on both the Victoria Line and the Northern Line. Control of the lines is entirely separate but SCs frequently cover for each other during comfort breaks and may sometimes assist each other when one line is busy and the other quiet. Their behaviour on these occasions provides not only insights into the relationship they have with each other but also into the implicit boundary or horizon of responsibility they operate within. One Northern Line SC covering for his Victoria Line colleague answered an external call but would not make a decision: "I know what I'd do if it was me, but it's not my railway." Technically, the SM has ultimate operational responsibility for the line but this is usually delegated to the SC without interference, so that the SC responsible for a particular line can be regarded as the ***only authority*** on that line (except for authorising TOs to pass signals at danger which is the responsibility of SOs). This means that other SCs (even those with more experience) will not encroach on that boundary of responsibility. They will only take a message and pass the relevant information on, perhaps offering advice if asked for it. Trainees and inexperienced SCs come to this understanding by watching how other SCs relate to each other. The function of the behaviour has its origins in the safety-critical attitude required by the work and in the efficiency that results from having just one SC in charge of a line, but it also reinforces the respect that SCs have for each other.

A similar example of inter-SC cooperation was observed when a Victoria Line SC (SC1) offered assistance during a passenger emergency alarm incident on the Northern Line. In general, all control room practitioners are highly skilled at listening out for operational information that is relevant to their role. They are sensitive to situations where they can assist and will offer to get involved. In this situation, it was clear the Northern Line SC (SC2) was having difficulty communicating over his radio – a known problem where a connection couldn't be made until after repeated attempts. SC1 offered to attempt connections leaving SC2 free to deal with other aspects of the incident. When the connection was made, SC1 informed all TOs of the incident then both SCs watched the situation unfold on CCTV. An unclaimed bag was removed but the train failed to leave. SC2 spotted that the doors in the car where the incident had occurred were failing to close (because they had been specially opened by either the TO or station staff). The train would not be able to depart until intervention by the TO. SC1 asked, "You gonna let him know?" (Note that this is not his decision but he prompts SC2 who is responsible.) SC2 replies, "He should know…" SC1 nods without replying. (Note: within reason, explaining the problem to the TO may have taken longer than allowing the TO to figure out the problem for himself – both SCs are aware of this.) Within a short time the two SCs spot the TO leaving his cab to check the doors and they make exasperated comments about how slowly the TO is walking! (Note: delays are the concern of the SCs not TOs). This episode illustrates the close working relationship of SCs, their shared knowledge and concerns, and the horizon of responsibility relating to a particular line observed by both practitioners.

After a period of classroom instruction, control room practitioners learn "on-the-job" under the supervision of a senior practitioner. A trainee SC may know the procedures for a particular type of incident but will learn what it is to be an SC from watching other SCs in action. This is evident in the following example. The general atmosphere in the control room is lively when the lines are quietly operating to timetable. The banter and horseplay is tolerated, even encouraged, partly to guard against boredom and partly to build team spirit and morale. Despite appearing not to be maintaining awareness of the state of the line all experienced staff are in fact acutely tuned to the cues that indicate that work is necessary. There seems to be a pride in this behaviour of participating in banter but being able to respond instantly to incidents if required, and it may have a purpose in practising the kind of multi-tasking that is useful in the job. One trainee SC who had been in the control room only a week was swapping jokes comfortably with Northern Line staff but then was suddenly faced with several incidents at once. Others carried on joking around her (without including her) but she hesitated. The trainer instead of asking for hush admonished her: "Keep your eye on the job. You've got a radio call waiting…"

The training may be supplemented by exercises (such as reforming a hypothetical service with paper and pencil) and by generic war stories aimed at providing useful examples, but crucially the social organisation of the work is learned through observing the relationship between SCs and between the SC and other staff both internal and external to the control room.

ISSUES

Key findings about the relationship that exists between SCs suggest that trainee SCs learn on the job what it is to be an SC. The organisational structure proposed by the upgrade will initially be new for everyone, and the established patterns of behaviour that demonstrate what is expected of new recruits will need to change, in particular with respect to the way in which horizons of responsibility are set to change dynamically as incidents develop.

The separation of Victoria Line and Northern Line control will have at least two implications. Firstly, there will be less experience to draw from in each location since inexperienced practitioners will have fewer experienced colleagues to watch and learn from, and the opportunity to observe incidents being dealt with on the other line will be lost. Secondly, the informal practice of SCs who are responsible for different lines covering for and assisting each other and will end, a situation that affects the Northern Line (with one SC) rather than the Victoria Line (with two Level 2 SCs). At the new Victoria Line control room the practice of SCs covering for and assisting each other may be made more complicated by the need to log in to or reconfigure equipment. The type of subordinate-superordinate collaboration observed between SCs of different lines will differ from the working relationship of Level 2 SCs on the upgraded Victoria Line because here the responsibility for line control will be shared.

9.5 The Development of Practice Model

SUMMARY

The development of practice here is concerned with the co-evolution of the artefacts and tasks that constitute Victoria Line control over the decades. The analysis starts with a high-level summary and a timeline diagram that represents key moments in the history of the technology and organisational structure. Each numbered timeline is then described in greater detail taking into account its significance and dependencies.

This level of the analysis concentrates on the period of approximately 50 years spanning the late-stage planning of the Victoria Line in the early 1960s, the official opening in 1968 and the 40 years of operation until 2008 just prior to the proposed Victoria Line upgrade in 2009. The legacy of technology that was in existence prior to the opening in 1968 is considered in terms of its direct effect on the technology that was chosen to implement the Victoria Line. The organisational structure, i.e. the way in which the line was staffed, has its origins in high-level operational decisions on matters of cost and efficiency. Major technological change and organisational change have occurred at the same time and closely influence one another. External events, in particular the King's Cross disaster of 1987, also influenced technological change and therefore the practice of the line control conducted using that technology.

The data in this section of the analysis comes from a recorded interview conducted with two senior London Underground employees both of whom have had extensive experience involving different roles and different lines. The data has been checked where possible and supplemented with information from Day (1969), Horne (2004) and Horne (2006).

Figure 21: Development of Practice (see next page)

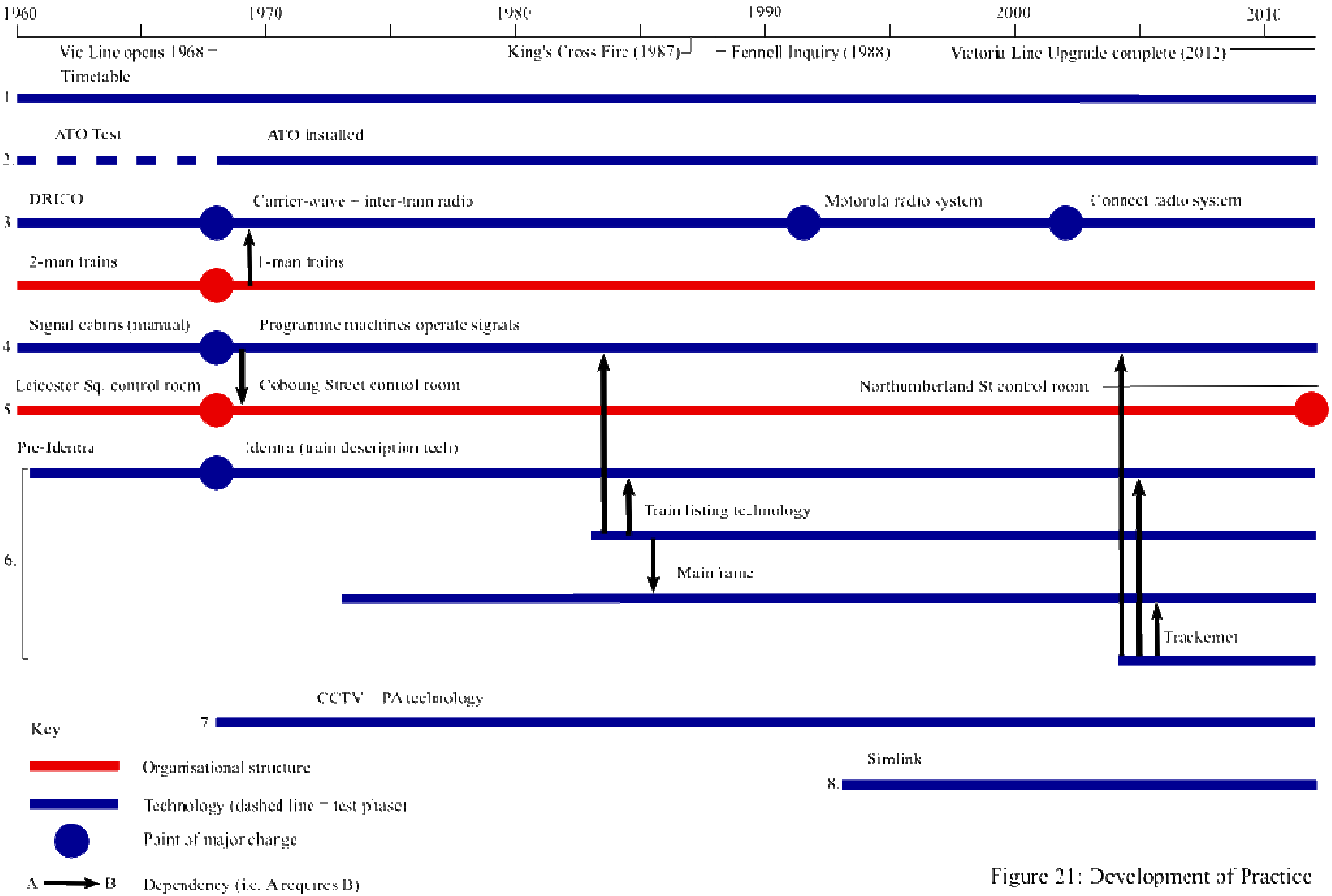


Figure 21: Development of Practice

DETAIL

1. Timetable

The main aim of the Victoria Line was to relieve passenger pressure from other lines and to form interchanges with other largely disconnected Underground lines and some overground services carrying commuters from outside of London. The first Victoria Line timetable was therefore constructed to be compatible with the timetables operational on other lines. The timetable as a concept has its origins in the organisation of earlier railway systems but has evolved to fit the rapid-transit system on the Underground where passengers do not need to consult it. In some instances on the Underground where the frequency of trains is low enough, passenger timetables are necessarily available to the public but these may differ slightly from the operational timetables used by line control staff. The main purpose of the timetable used in line control is to obtain the most efficient use of train crews – TOs are rostered according to the timetable and this working structure has to take into account the framework of agreements that apply to TOs regarding periods of continuous working between breaks etc. When the timetable is replaced by a special service during an incident, the workload of the DMT is increased because he/she must coordinate the special service with rules regarding the framework of agreements. Another purpose of the timetable is to obtain the most efficient use out of trains, for example, journeys are planned to coincide with stock maintenance so that trains are delivered to the correct location at the correct time. Timetable information exists in the programme machines, the Cobourg Street mainframe and the physical sheets used by staff (see section 9.3.3 for more information on how the timetable is used by control room staff). The timetable can be regarded as the “informational backbone” of the line in that without it efficient service would not be possible. It evolves slowly and in response to increasing passenger demand where technological change makes a greater capacity service possible.

2. Automatic Train Operation (ATO)

During ATO the train receives coded impulses from the track that cause it to accelerate, coast and brake, obeying all instructions along the way, for example slowing down or stopping and restarting as required if there is another train ahead or a speed restriction is in force. The TO can drive manually in the event of ATO failure. The train cannot run unless it receives coded impulses, i.e. brakes will be applied if the train fails to receive codes. The state of track circuits ahead (e.g. showing whether the line is occupied) automatically determines the code to be fed into the track section. On a typical run between stations, the train has to start and run under power to a fixed point from where it can then coast to the next station.

Following successful tests of 1960s stock installed with ATO technology, the first passenger-carrying ATO trains were operated on parts of the District Line and Central Line before the decision was taken to equip all stock for use on the Victoria Line which when it opened in 1968 was the world’s first fully automatic passenger-carrying railway. The relatively long time taken to commit fully to such technology is partly attributable to “signal assurance”, i.e. the need to convince decision-makers that the system was completely safe. This cautious approach results in incremental technological change and characterises much of the change on the Underground system. The drive to introduce ATO is linked to the organisational decision to move from two-man operated trains to one-man operated trains (i.e. with the loss of the guard).

The main reason for using ATO is the improved efficiency that results from designing out TO variation. Each TO may drive the same section of track in a different way, accelerating and braking in different places. Therefore the only variable following the introduction of ATO is platform-dwell time because this is managed by the TO. This improved efficiency can be exploited in "moving block" scenarios where the following train can decelerate into the station on the same section of track that the leading train is accelerating out of the station upon, a situation that is not possible with conventional signalling where only one train can occupy a section of track at a particular time. Since ATO takes advantage of the pre-calculated optimum set of codes that propel a train, it also saves power, which is increasingly important as the cost of energy rises.

3. Communication – the evolution of radio

The tunnel telephone was the first means of communication available from Underground trains and was originally designed as much to enable TOs to gain information as well as to inform the controller of an emergency. However by the 1930s, the tunnel telephone's only use was in the event of emergency, and communication was only possible with a simultaneous removal of traction current, a function it still performs today. The period after the Second World War saw the introduction of Drico (short for driver-controller) which was grafted onto the tunnel telephone system and allowed communication to take place without a removal of traction current. As a system Drico suffered from a series of limitations: the train had to be stationary; the train had to be in a tunnel; the TO had to initiate the call; and Drico was notoriously unreliable if more than one TO attempted to use it at the same time. An alternative primitive means of communication existed whereby the TO could send the guard forward to a signal telephone or a station. The decision to operate one-man trains depended on finding an improvement in communications technology.

Radio technology was unworkable in the 1960s because signals were absorbed by the tunnels. The solution was Carrier Wave technology implemented on the Victoria Line. Carrier Wave worked by sending speech signals through the conductor rails rather than aerials. It was more reliable than Drico but still was unusable if the leading car was on any of the current-rail gaps that existed on the Victoria Line or if a short-circuiting device was placed over the current rails in an emergency. Its main advantage over Drico was the ability for either TO or signal regulator (not controller) to initiate the call. The system's limitations were exposed during the Fennell Inquiry following the King's Cross Fire and the system was replaced in late 1992.

Another system introduced onto the Victoria Line at the same time as Carrier Wave technology in response to one-man train operation was the inter-train radio, the purpose of which was to facilitate communication when a faulty train needed assistance or shunting from another train behind. The system only worked when the two trains were coupled but proved to be of little practical value and was phased out in the 1980s.

The Carrier Wave system proved the utility of continuous communication but was expensive and had to be tailored for London Transport. Radio technology was installed and developed on other lines and the Victoria Line was the last line to receive a radio system which replaced Carrier Wave. Radio systems were deliberately separate for each line to avoid potentially dangerous confusion, particularly where train numbers were common between lines. The Victoria Line radio system was supplied off the peg by Motorola and was a success largely because it was installed and maintained by these external specialists. The Motorola system was still only used between TO and signal regulators in the control room. This organisational arrangement was kept in place because there were two regulators to take calls during busy periods as opposed to one controller.

The rapid evolution of communications technology was a factor in the number of disparate radio systems which could not provide all the communication links required by the Underground during the 1990s. Private finance in the mid-1990s paved the way for a single comprehensive network-wide system known as Connect which was installed on the Victoria Line in 2004. At this point SCs as well as SOs had access to radio communications. A further advantage of the Connect system was the ability to make use of train location information displayed on the despatcher screen (see section 9.3.3).

4. Signalling

One implication of ATO is that signalling on the Victoria Line is different in some respects to other lines, for example, fewer fixed colour-light signals and no train stops (i.e. the safety equipment which applies the brakes if a red signal is passed) are required. On the Victoria Line a signal passed at danger would mean a lack of codes supplied by the track and therefore immediate braking. At junctions and crossings there is an interlocking machine that ensures that the points and signals cannot be set up in any unsafe configuration. Originally on other lines, a signalman housed in a signal box would operate levers and buttons to instruct the interlocking machine to set up the required routes. On the Victoria Line, this function is performed by the programme machines each of which contains a plastic roll with a pattern of punched holes relating to the full timetable. The introduction of programme machines paved the way for a single regulator to take responsibility of the signalling on the line and was a factor in the need for a new control room (see 5).

5. Evolution of control room structure

Prior to the Victoria Line, the controllers for all lines were housed in one control room based at Leicester Square. There were no signal regulators (SOs as they are known now). Each controller had a partitioned desk and could overhear other controllers to maintain an awareness of what was happening on other lines. They had no visual aid to the state of lines and were equipped only with phones (primarily to contact remote signalmen) and timetables.

The newly opened Victoria Line had a dedicated control room at Cobourg Street which follows approximately the same organisational structure as it does now. Originally only one signal regulator was positioned in front of the controller’s desk facing the FLD. Two regulators were later introduced for controlling signals during a busy incident. Only one SO is needed even now to monitor the line when the service is stable and running according to timetable. The Line Information Assistant or LIA (now known as the SOI) was present at a separate desk positioned to one side of the FLD by the door. The LIA's role was essentially the same if more basic – he was just equipped with a phone to contact station supervisors in the event of an incident and was expected to overhear the information he required. The Cobourg Street control room is to be vacated by the Victoria Line control staff when the upgrade is complete in 2009. At the new control room, a different organisational structure is planned with the tactical SO and strategic SC roles merging into one role, with the SM taking on some extra strategic responsibility.

The relatively slow evolution of control panel technology in the control room is partly attributable to the persistence of the organisational structure. The controller's desk has had the most radical changes (at least two major refits). The original controller's desk was dominated by a key-and-lamp telephone control panel for facilitating direct links to frequently required contacts. There was a telephone link between controller and regulator but it wasn't initially recorded. Telephone technology has evolved to give the SC access to two touchscreen telephones (first installed in the mid-1990s) with a manual telephone back-up. The original regulator's control panel has never been replaced. Initially the regulator had access to a sloping panel mounted on the desk that controlled the mode of programme machines. If a programme machine was put into push-button mode that required it to be operated manually, a secondary panel housed in the desk drawers could be pulled out to operate signals. This equipment arrangement fitted the designer's vision that the programme machines would be able to function without frequent intervention. These panels were subsequently bolted on top of the slope panel once it was realised that intervention was required more frequently than first thought (and because drinks were spilled on them!)

6. Train identification technology

Prior to the Victoria Line the description of the train (i.e. its destination) was fed into the signalling system by the signalman at terminus start. The description would precede the train automatically from signal box to signal box until the train reached its destination. The train description would be used by station and signal staff to identify a train and to operate platform displays for passengers. On the Victoria Line, a system was introduced to allow the train description to be input onto the train itself. This Identra technology (unique to the Victoria Line) allows the train to pass its destination information (but not a train number) into coils on the track so it can be picked up by the programme machines. The programme machine compares this information against the destination information it holds for the next train it's expecting according to the timetable and transmits mismatch warnings back to the control room. On some lines even now (for example the Hammersmith branch of the Hammersmith & City Line), there are "black holes" where signalling system train descriptions are not available. Signallers stationed at remote signal boxes have to assume that a train entering these black holes is what is timetabled unless another signaller phones to say otherwise. A Manual Electronic Logging system (MEL) improves the communication of information to a certain extent by implementing a web-based version of the paper logging sheets that help to track train movements but MEL does not replace phone communication. Controllers that manage lines with black holes may ask a station supervisor to physically go to the platform and read the ID of the train waiting there.

Some isolated experiments with number recognition cameras have been performed without success.

The information on the train-listing screen in the control room (available to SOI, SC and SO) is derived from and dependent on the programme machines, Identra and a mainframe computer installed in the 1970s which marries train number and description and calculates delays of individual trains. The mainframe is hardwired into every track circuit on the Victoria Line so it can also detect the presence and movement of trains. Prior to the introduction of train listing screens, the regulator relied on written notes to maintain awareness of where particular trains were. The train listing technology has undergone a number of minor upgrades since it was installed in the 1980s.

The information shown on TrackerNet screens which show the apparent location of trains on a diagram similar in layout to the FLD is derived from exactly the same sources that drive the train listing screens.

Control room staff now rely more heavily on Connect to identify trains and their locations, however Connect shows only train number, not train description information.

7. CCTV + PA technology

CCTV was an innovation introduced first on the Victoria Line in station control rooms and at Cobourg Street to assist in crowd control and emergencies and is closely coupled with the PA system designed to complement it. The priority of the PA system was originally in favour of the Cobourg Street controller who had precedence over the station controller. This hierarchy was reversed for safety reasons so that station staff evacuating a platform in an emergency would not have announcements overridden. The change in organisational structure is probably made possible by improvements in radio technology that improve communication between control room and station.

Two 19-inch monitors were installed at the Cobourg Street control room. They were positioned away from the controller’s desk but could be remotely operated to select camera view of platforms at any Victoria Line station.

An ear-piece on the controller’s desk gave the controller access to local announcements being made a specific stations, a facility which is no longer made available. This is an example of how information is filtered out to reduce the complexity of the SC role and is probably possible because of improved radio communications with staff at the station.

The success of CCTV has resulted in its proliferation (more camera views) and the positioning of one monitor on the SC’s desk and one on the SOI’s desk.

8. Simlink

The Simlink system was introduced on the recommendations of the Fennell Report. Prior to the King’s Cross disaster communication links between control rooms were poor. Every station has an “owning line”, for example King’s Cross was “owned by” the Metropolitan Line. This meant that everything that happened at King's Cross was relayed to the Metropolitan Line controller whose responsibility it was to inform other line controllers. The failure of this communication system resulted in fatalities when other line controllers continued to direct trains to King's Cross during the fire. Critical information is now relayed to Network Operations Centre (NOC) and this is propagated to all line controllers via the Simlink system. The installation of this system can be viewed as a response to the way in which control was distributed to separate control rooms following the phasing out of the original control room at Leicester Square that housed controllers responsible for all lines.

TRENDS AND ISSUES

The development of practice is characterised by a number of trends which suggest implications for the proposed Victoria Line upgrade changes.

It is sometimes not possible to identify the exact nature of the causal forces at work for the development of a practice such as line control. An attempt has been made on the timeline diagram to indicate the direction of dependencies but this is an interpretation only. For example, it is the opinion of the interviewees that one-man trains **necessitated and therefore drove the introduction of** more comprehensive and reliable communication links with the control room, but it may be that improved communications technology merely added weight to the decision to introduce one-man trains. What remains clear, however, is that the organisational change and the technological change occurred at the same time and that a dependency exists. In reality the dependency is probably bidirectional. In the case of the proposed changes, a decision to merge the roles of SC and SO undoubtedly necessitates a fundamental change in the technology required to perform the task of line control. Given the tight coupling that historically exists between changes in organisational structure and technology on the Underground, the redesign of the tools must fit the redesign of the organisation of the work. In other words, the two aspects must be co-designed otherwise a rift will open between the needs of the practitioners and the capabilities of the tools. For example, a decision to revert to separate SC and SO roles after the equipment has been designed to facilitate one SC carrying out both strategic and implementation work is likely to cause usability problems.

Organisational and technological change on the Underground has historically been slow and incremental mainly for reasons of cost and safety. The fact that different lines operate and can develop independently of each other has encouraged this incremental nature. For example, the introduction of Carrier Wave proved the case for improved continuous communication and paved the way for experimental development in radio technology. Each significant improvement justified the introduction of a newer radio system to the line that was undergoing upgrade work at the time. The rapid pace of change in this communication technology compared to the pace of upgrades could actually be exploited so that isolated lines could be the test-beds for change prior to a more extensive roll-out. The downside was the proliferation of disparate systems and lack of standardisation across the Underground as a whole. In this sense, the Victoria Line upgrade can be seen as a high-profile test of merging SC and SO roles and of the technology aimed at facilitating this organisational change – one that must succeed if it is to be introduced to other lines.

Further evidence of the incremental nature of change on the Underground can be seen in the way existing technology, such as the train-listing screens, is left in place as a back-up or complement to newer technology, such as the Connect radio screens. Taken against the sedate evolution of the Victoria Line control room over forty years, the relocation, change of equipment and organisational structure of the proposed upgrade represents the most significant single change in its history.

The general trend away from a distributed and towards a centralised system of control can be identified from the wider changes instigated by the opening of the Victoria Line in 1968. The replacement of remote signal cabins and staff by programme machines, the improved communications between TO and control room, and the introduction of technology such as CCTV drew control and responsibility into one central location. The proposed changes of the upgrade continues that trend further by centralising the tasks of line control amongst potentially fewer practitioners overall. Given the likely increase in passenger demand and therefore train frequency, this will only be possible if the technological support is improved in terms of reliability and information accessibility. For example, unless the task of locating and identifying particular trains is integrated, i.e. without requiring the coordination of multiple sources of information, performance is likely to suffer particularly during line control incidents.

Interestingly, the further "centralisation" of tasks implied by the merging of SC and SO roles will, as the line becomes busy during an incident, result in a "distribution" of control, particularly in terms of responsibility, as the line control is shared on a geographic basis amongst controllers. New technology external to the control room will allow the frequency of trains and therefore the complexity of the service to increase, making this shift in organisational structure inevitable, especially during incidents.

Furthermore, at a different level there is a simultaneous counter-trend towards distributed rather than centralised control in terms of the control of individual lines. The move from the original Leicester Square control room (that served all lines) towards individual control rooms (each serving usually one line) has continued since the Cobourg Street control room was introduced. This organisational change reflects the understanding that different lines can (and often should to avoid confusion) be operated separately despite the catastrophic effect of the loss of inter-line communication during the King's Cross disaster. Simlink and NOC are the necessary technological and organisational solutions to this loss of communication. A loss of communication should also be expected from the organisational change proposed by separating the centres of control for Northern and Victoria Lines. Operational performance may not suffer directly as a result of this change because the lines are controlled separately and Simlink will ensure the vital information still flows between them. However, the current proximity of the centres of line control gives some additional benefits that may be lost following the upgrade (see section 9.4).