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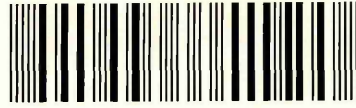
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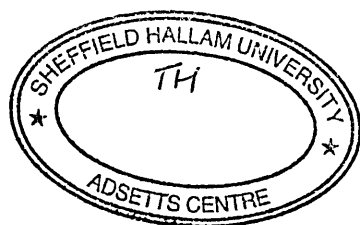
# Off-line Condition Monitoring of Powered Train Doors

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A thesis submitted in partial fulfilment of the requirements of  
Sheffield Hallam University  
for the degree of Master of Philosophy

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Collaborating Organisation: Interfleet Technology Limited



## Abstract

Powered passenger train door unreliability is a major source of in-service delay and cancellation to passenger train services. This unreliability costs UK Train Operating Companies significant amounts of money through Railtrack charges, customer compensation payments and loss of revenue as well as door maintenance and repair procedures. The successful and reliable identification of incipient powered door faults could therefore help to reduce these charges and subsequent maintenance costs, increase train reliability and potentially reduce safety-related incidents.

This thesis presents the research and development of an off-line condition monitoring tool for electric powered passenger train doors, the Door Analysis Tool. The Door Analysis Tool was developed through a two-year, collaborative TCS project between Sheffield Hallam University and Interfleet Technology, an international railway engineering consultancy. The project was partly funded by the Department of Trade and Industry.

This thesis focuses on a number of primary areas of work, namely:

- Introduction to powered train doors and condition monitoring in the railway industry;
- Identification of suitable data collection and condition monitoring equipment for powered train doors;
- Development of suitable data analysis and interpretation algorithms;
- Development of a commercially viable prototype condition monitoring product for powered passenger train doors, the Door Analysis Tool;
- Validation of the Door Analysis Tool through theoretical and practical testing;
- Identification of further development opportunities and further future work.

The Door Analysis Tool uses clamp-on current probes to measure the door motor current characteristic and traction interlock status during opening and closing cycles to monitor the performance of train doors. It offers a range of opportunities to different parties within the railway industry to help reduce the impact of powered train door unreliability and thereby improve train performance through the identification of faulty train doors prior to costly in-service failures.

The practical testing of the prototype Door Analysis Tool showed that it functions as intended in a train maintenance depot environment and that it is capable of collecting, analysing and classifying data relating to train door performance.

The theoretical tests presented the prototype Door Analysis Tool with nine different sets of data, each representing a range of faulty and fault-free door operations. The Door Analysis Tool was able to correctly classify six of the nine tests. Three of the tests incorporating minor fault conditions were not highlighted by the door performance classification, however all of the theoretical faults were identifiable through inspection of the analysis parameters, which can be stored after each test. The sensitivity of the Door Analysis Tool analysis routines can be adjusted to tailor the tool to different systems.

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## Abbreviations and Symbols

a.c.	Alternating Current
ADC	Analogue to Digital Converter
ASCII	American Standard Code for Information Interchange
DAT	Door Analysis Tool
d.c.	Direct Current
DMU	Diesel Multiple Unit
EEPROM	Electrically Erasable Programmable Read Only Memory
EMU	Electric Multiple Unit
GPS	Global Positioning System
HST	High Speed Train
ISP	In-System Programming
LCD	Liquid Crystal Display
LED	Light Emitting Diode
OEM	Original Equipment Manufacturer
Op-Amp	Operational Amplifier
PC	Personal Computer
PCB	Printed Circuit Board
RAM	Random Access Memory
RTC	Real Time Clock
SDO	Selective Door Opening
SHU	Sheffield Hallam University
TCS	Teaching Company Scheme
TOC	Train Operating Company

## 1. Introduction

Powered passenger train door unreliability is a major source of in-service delay and cancellation to passenger services. This unreliability costs train operating companies (TOCs) significant amounts of money through Railtrack charges, customer compensation payments and loss of revenue as well as door maintenance and repair procedures. The successful and reliable identification of incipient powered train door faults could therefore help to reduce these charges and subsequent maintenance costs, increase train reliability and potentially reduce the likelihood of safety-related incidents.

There are a large number of powered train doors currently in use in the United Kingdom and even a small fleet of trains contains a large number of doors. Although an individual powered train door can be generally quite reliable, the high number of doors on a train, combined with their interconnection within the traction interlock safety circuit, makes powered passenger doors one of the largest sources of train unreliability. Condition monitoring of powered train doors could help to identify problems or faults before they occur in passenger service. However, for condition monitoring to be a commercially viable engineering solution, the technique must require no retro-fitting of components and no modification to train systems, since this would be prohibitively expensive due to the high number of doors. This implies that the solution must exploit non-intrusive, non-continuous monitoring techniques, which can be employed whilst trains are not in passenger service. The solution must also be portable and self-contained as well as simple and quick to use so that every door in a fleet of trains can be effectively monitored.

This thesis discusses the development and testing of an off-line condition monitoring device for use with powered train doors, which is based upon the work undertaken by Simon Perkin as part of a Department of Trade and Industry-funded Teaching Company Scheme (TCS) project. The project was a collaboration between Interfleet Technology Limited and Sheffield Hallam University (SHU). The thesis details the identification of a suitable condition monitoring technique, suitably tested and refined through practical depot testing, as well as the refinement of data analysis algorithms to identify normal and abnormal door operation. The thesis finally presents the development of a microprocessor-controlled off-line condition monitoring tool for powered train doors.

## 2. Powered train doors

This chapter will focus on the fundamental area of powered train doors, briefly reviewing their history and examining the main advantages and disadvantages of powered train doors in comparison to older slam doors to explain why they have become a standard feature of modern railway vehicles. Additionally, the main features and components of electric and pneumatic powered train doors will be discussed. The commonalities and fundamental differences between these two types of door system will be explained, allowing the benefits and drawbacks of both systems to be identified.

### 2.1 A brief history of powered doors

Powered train doors are now a standard feature of modern and new-build trains, however powered doors first entered general mainline passenger service in 1938 on the LMS Mersey-Wirral electric multiple unit (EMU) stock<sup>1</sup> (figure 2a).



*Figure 2a: Photograph of a LMS Mersey-Wirral Electric Multiple Unit, 1938<sup>1</sup>*

Before the widespread introduction of powered doors, passenger trains were fitted with doors that had to be manually opened and closed by the passengers themselves, known as slam doors. This type of door is still in use today within the

UK rail industry, fitted to the majority of high speed train (HST) passenger coaches (Mark 2 and Mark 3 type), which are currently used on a high proportion of long distance, inter-city services. Slam doors passenger vehicles are also still in operation on a range of suburban rail vehicles (e.g. Class 101 diesel multiple unit (DMU), 308 EMU or 411 EMU). The Rail Safety Regulations 1999 require that all Mk 1 rolling stock (slam door) rail vehicles must be withdrawn from service, and that all trains must be fitted with central door locking by the end of 2004<sup>2</sup>.

In the mid 1990s, all high-speed trains featuring slam doors were fitted with a central door locking safety system. This modification successfully reduced the number of injuries and deaths caused by passengers falling from moving trains at, or between, stations. It also helped to reduce accidents caused by passengers attempting to board moving trains. The system allows the train driver or guard to lock, or unlock, every external passenger train door from a single location and signified the continuing process of transferring door control away from the passenger.

## 2.2 Powered doors versus slam doors

Powered train doors offer a number of distinct advantages over the older slam type of door, which explains why powered doors have become a standard feature of modern trains. These advantages can be summarised as follows:

1. A passenger inside the train or on the station platform must only push a single button in order to open or close a train door.
2. The ability of passengers to operate powered train doors can be restricted in order to minimise the risk of incidents that could result in injury or death.
3. Powered train doors are not fitted with opening windows. This reduces the risk of injury or death to passengers and stops objects being thrown from the train.
4. The train guard or driver can remotely operate all, or a selection of, the doors on the train. Consequently, platform staff do not have to close any open doors before the train can leave a station, reducing stopping times and total journey times whilst maximising the likelihood of a punctual service.

5. Powered doors can automatically close after a defined period of inactivity, helping to maintain optimum levels of passenger comfort (e.g. temperature and humidity) throughout a train journey.
6. Powered doors imply a certain level of technology to the fare-paying public. This may play a significant role for TOCs in helping to generate and maintain the company corporate image. Although image is traditionally associated with service punctuality and reliability, in-train features, service and passenger comfort, the first and last part of a train that all of the passengers will encounter will be the train doors.

Although powered train doors would appear to be a clear technological improvement upon basic slam doors, they introduce new problems as well as operational and safety issues. The typical disadvantages of modern powered passenger train doors are summarised below:

1. Even basic powered train doors are much more complex in design and operation than traditional slam-type doors. This is because they move through complex paths, must be controlled locally and remotely, feature automatic locking and other safety systems. Consequently they are normally more difficult to set-up, maintain or overhaul, which leads to poor in-service performance and reliability<sup>3</sup>.
2. External powered train doors are safety-critical components, which must remain operationally safe at all times. This means that if a fault does occur, safety must not be compromised (i.e. the doors must fail safely). The doors must only open when a command is given by the driver/guard and, even then, only when it is safe to do so (when the train is stationary). The doors must remain closed and positively locked whilst the train is not at a station, however the passengers must be able to easily egress from the train in an emergency. Powered train doors must be able to detect obstructions, such as a piece of baggage, a pushchair or a hand, normally during the door closing cycle and must allow the obstruction to be removed before the train can depart. The force capable of being exerted in the direction of travel by any part of the door or exposed door mechanism, during either opening or closing, should preferably be in the range 80 N to 100 N and should not

exceed 120 N' <sup>4</sup>. All of these features demand 100% reliable operation and the failure of any one of the features can cause a train to be withdrawn from service.

3. Powered train doors are normally designed to tight mechanical tolerances and so are quite sensitive to changes in their immediate environment. The dynamic response of the train body whilst in-service (due to passenger loading or wheel-rail interaction for example), temperature changes or simple vandalism and rubbish can all lead to abnormal or incorrect operation.
4. As the complexity of the powered train door increases, so naturally does the cost of each installation. This is true for the initial equipment cost as well as for the cost of spares, replacement components or overhaul servicing. However, the total cost of a single powered train door is negligible and incidental in comparison to the cost of a new train.

Despite these problems, powered doors are now considered a standard component of modern trains and new trains must feature powered passenger train doors rather than slam doors. From their initial introduction into passenger trains, powered doors continue to be developed to incorporate new technology if it can offer improved performance or additional features. An example of this is the selective door opening system (SDO) on the Adtranz Class 375 Electrostar fleet of trains. This system uses the global satellite positioning system (GPS) to identify the current location of the train and to control the opening of the appropriate passenger doors at the next station on the route. SDO aims to improve passenger safety for train services that operate at stations whose platforms are shorter than the train, which is a particular problem in the south of the United Kingdom.

However, powered doors continually prove to be one of the most unreliable on-train systems. For modern doors, this may partly be due to the use of inappropriate technology that is simply unreliable or that has not been properly developed for use within a harsh railway environment<sup>5</sup>. Other factors concern the modular manufacture and assembly of modern trains. Powered doors are

normally designed and tested by a sub-contracted manufacturer, often in isolation from the train. The doors normally require highly rigid mountings in order to operate correctly and reliably, however the train body is designed to flex and deform under normal train loading and operating conditions, resulting in door systems operating outside of the design tolerances. Incorrect maintenance, overhaul or fault-finding procedures as well as poor original design all contribute to the problem. Finally, powered doors suffer a significant amount of passenger abuse, either as deliberate vandalism or just through normal usage, and are often exposed to extreme temperature and weather conditions on a daily basis. Irwing discusses the causes of powered door unreliability and suggests possible improvements or solutions in more detail<sup>5</sup>.

## 2.3 Major components of a powered train door system

In order to successfully condition monitor any electro-mechanical component, it is firstly necessary to fully understand the system. This section will identify the major components of a generic powered train door system, explaining their operation and purpose.

### 1. Door leaves

These are the most visible components of a powered door system, comprising the door panel and window structure. Passenger powered doors tend to have two leaves that move in opposing directions, providing a large portal for passenger embarkation and disembarkation. Although less common, single leaf passenger powered doors do exist (e.g. Class 156, British Rail Mark 4 passenger coaches or Eurostar Class 373), though the width of the leaf is normally slightly larger to provide adequate portal dimensions. Powered cab doors are always of a single leaf design that is a similar width to a single powered passenger door leaf. For safety reasons, cab doors are normally only powered for the first portion of the door opening motion and the driver must then physically fully open the door. This stops drivers from being injured if they open the door whilst leaning out of the cab door window.



## 2. Power source

This is arguably the most important major component of a powered door system, without which it would not function. Train powered doors are fitted with pneumatic actuators or electric motors, because both compressed air and electricity are readily available on all trains.

Compressed air at a main reservoir pressure in the range of 7 bar to 8 bar is used on all railway vehicles as part of the braking system and so adapting the system to service other on-train functions, including powered doors, is a logical progression. Linear pneumatic actuators are the common power source for pneumatic doors (e.g. Class 507/508 or Class 313), however rotary pneumatic actuators are sometimes also used (e.g. Eurostar Class 373 passenger powered doors).

Similarly, electricity is universally available on both diesel (e.g. Turbostar Class 170) and electric trains (e.g. Heathrow Express Class 332) and is extensively used to operate and control nearly all aspects of trains. Electric motors, normally d.c., can be supplied directly from the 110 V d.c. train line or alternatively from 24 V d.c., both of which are commonly available on trains.

## 3. Transmission and mechanical linkage

It is necessary to transmit mechanical power from the pneumatic actuator or the electric motor to the door leaves so that they can be opened and closed. This can be achieved in any number of different ways in various mechanical configurations, but common examples are toothed belt drives (e.g. Class 507/508), lead screw and gearbox (e.g. Class 323 or Class 332) or lead screw and toothed belt (e.g. Class 333). In addition, mechanical linkages, hinges and rollers are used to restrict door degrees of freedom whilst helping to guide the door leaves during operation.

#### 4. Mechanical locking mechanism

The locking mechanism is the main safety feature of passenger train doors, which also forms part of the train traction interlock circuit (see below). Each train door must be fitted with a mechanical locking mechanism that physically stops the doors from being opened at an inappropriate time either accidentally, or by a passenger (inside the train or on the station platform). However, in an emergency, it must be manually possible to release the locking mechanism and open the train doors to allow passenger egress.

#### 5. Control system

A control system is necessary for each powered door to control the operation of the door. For pneumatic doors, the control system may simply consist of a number of valves and regulators, which control the flow of compressed air from the main train reservoir to the door actuator cylinder. Modern electric doors feature dedicated control units, which contain a printed circuit board (PCB) featuring software-controlled microprocessors. The microprocessors rely on electrical signals from sensors or microswitches to correctly control the powered doors.

The control system must also be able to interact with other systems, such as obstruction detection, emergency egress / access, train functions and input from the passengers via the door control panel. Consequently the control system must not be able to compromise the safe operation of a powered door and for this reason, the safety-critical aspects of door control have always been controlled by hardwired electrical circuits, rather than software. The response of an electric circuit containing switches and relays to different system inputs can be analysed and predicted, whereas the behaviour of complex software in response to any number of different inputs, is much more difficult to guarantee.

#### 6. Traction interlock circuit

The traction interlock circuit is a major safety feature of all passenger trains that operate on the United Kingdom rail network. It ensures that all of the external train doors (powered or slam) are correctly closed and locked

before the driver is able to gain tractive power. The traction interlock system is an electrical circuit connected in series to a number of microswitches that are fitted to each external door. When a door is closed and locked, the microswitches complete the traction interlock circuit locally and so consequently all of the switches for each door on the train must be correctly operated in order for the driver to gain tractive power. Conversely, if the traction interlock circuit is broken whilst the train is not at a station, the train brakes will be automatically applied. The circuit will be broken if a door opens in traffic, due to a microswitch fault or in response to a passenger operating an emergency egress device.

## 2.4 Pneumatic doors versus electric doors

Until the early 1980s the majority of, if not all, powered train doors utilised pneumatic systems as the power source. This was because compressed air was readily available on trains and probably partly because railway engineers were familiar with pneumatic actuators and the associated pneumatic system components. Control methodologies enabling the powered doors to meet the operational requirements were well understood, as were the common types of problems, maintenance requirements and overhaul procedures. In comparison, the technology required to implement electric doors was still new and untested in a railway environment and would lead to more complex, and consequently more expensive, powered door systems. However, as the component cost of microprocessor technology has reduced whilst improving system reliability, more fleets of trains were introduced that featured electrically powered train doors. Currently, a high proportion of new build trains feature electric powered doors and this trend seems set to continue in the near future. This section will highlight the advantages and disadvantages of both types of system.

With respect to the performance of a set of powered doors, an electric system offers a much greater degree of control over the velocity and acceleration than the pneumatic counterpart, as detailed by Morvan<sup>6</sup>. Ideally a door will open at a near constant velocity, which is difficult to achieve with a pneumatic actuator, but can

be accurately controlled using a motor in conjunction with an encoder to feed-back the real-time position of the door. It is also difficult to accurately control the final position of the pneumatic actuator piston (and hence the door leaf) without using complex control circuits. As a result, pneumatic doors tend to open and close quickly and jerkily, or slowly and smoothly. In comparison, electric powered doors can be accurately controlled during the complete door operating cycle using software in accordance with the demands of the train operator or in line with current legislation. The door control software can also be upgraded to improve the door performance, if necessary.

Compared to the current drawn by traction motors and other current-intensive train systems, electric powered doors have minimal power requirements and all of the doors could operate at the same time with no observable affect on the performance of other on-train electric systems. Conversely, the operation of one electric door will not affect the correct performance of another electric door on the train, which is not necessarily true for pneumatic doors. If the air demand from other train systems is high, then the performance of pneumatic doors can be compromised.

Electric powered doors are also able to offer a much wider range of ancillary features without the need for extra components. Examples are obstruction detection, self-diagnosis and fault detection, system monitoring and event logging, all of which can be achieved by an electric door electronic microprocessor, but which would need to be added as a secondary system for a pneumatic door system. The introduction of these secondary components, such as transducers or microswitches, can adversely affect the reliability of the door system that they are attempting to improve if their reliability is equal to or less than the reliability of the door system.

The maintenance and overhaul requirements of both systems are also markedly different. Major pneumatic components, such as the actuator components, need to be lubricated, replaced or cleaned on a periodic basis (typically based upon either time in service or mileage). This often requires the entire door system to be dismantled, which reduces the availability of the train and increases the likelihood

of introducing new faults into the system. In comparison, electric motors require little or no maintenance, though it is advisable to periodically check for misalignment or component wear. A disadvantage of microprocessor-controlled electric doors is that it is much more difficult to diagnose and correct electronic hardware or software-related problems, which can lead to the philosophy of simply renewing suspected faulty components if they are within a warranty agreement.

Based upon all of these factors, it is difficult to accurately compare the financial implication of selecting either an electric or a pneumatic door system. It is likely that the initial costs of an electric door system are much greater due to the higher complexity of components, such as the electronic control unit. This cost has to be offset against the greater operating, maintenance and overhaul costs of pneumatic door systems. The final financial factor to be considered, though often overlooked, relates to the cost of installing and operating a suitable power generation system (e.g. compressor or power converter)<sup>6</sup>.

## 2.5 Powered door configurations

One of the first decisions that must be made when selecting or designing a powered door system for use on a train is the door configuration. There are four basic configurations or types of powered door, which describe the motion of the door leaves and the configurations are generally independent of the door power source. This section will discuss the features of each door configuration (sliding, sliding plug, swing and folding doors) as well as the advantages or disadvantages of each system.

### 2.5.1 Sliding doors

This configuration features door leaves that move in opposing directions in a plane parallel to the side of the train. The door leaves are slightly recessed with respect to the train body so that they can slide into a pocket formed between the inner and outer skin of the train. This type of configuration is

commonly used in conjunction with linear pneumatic actuators, which are ideally suited to generating the necessary door leaf one-dimensional motion. The linear nature of the motion normally results in the simplest transmission and linkage arrangement of the three types of door configurations.

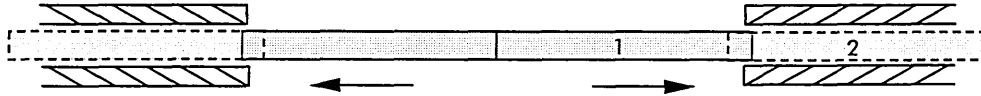


Figure 2b: Diagram showing a typical sliding door opening cycle

A disadvantage of sliding doors is that it is extremely difficult to successfully seal between the door leaf and the inner/outer skins and so a common problem for this type of powered door is therefore moisture, dirt or debris ingress into the door pockets. This can lead to operational problems and can reduce the life of the different components, either through increased wear or corrosion.

Sliding type powered doors have been in general use on trains since the 1930s and the system is commonly found on older UK rolling stock due to its simplicity. The simple door motion is ideally suited to rapid operation, for example on suburban and metro applications featuring frequent stops and high passenger densities<sup>7</sup>. Examples of rolling stock that use this powered door configuration are:

- Class 507/508 EMU (pneumatic doors)
- London Underground EMU (pneumatic doors)
- Class 150/2 DMU (pneumatic doors)
- Class 313 DMU (pneumatic doors)

### 2.5.2 Sliding plug doors

This configuration is similar to sliding doors and is currently the most common door configuration for new passenger trains. When closed, the doors sit flush with the body of the train, presenting a continuous smooth surface. This is a major factor for the popularity of this configuration, since it

results in an aesthetically pleasing smooth side to the train and an improved seal against weather and noise.

As before, the name of the configuration is derived from the door motion, which is predominantly perpendicular to the train side (unplugging) as the doors first begin to open. When the doors have unplugged from the train body, the door leaves move in opposing directions (sliding) in a plane parallel to the train side until they are fully open. Seals around the edges of each door leaf also effectively stop the ingress of moisture, dirt or debris into the train and the door sub-system as well as providing good resistance against pressure pulses. Consequently, the complexity of the actuation mechanism and the associated set-up problems are the main disadvantages of sliding plug doors, which are otherwise extremely robust and suitable for modern train applications.

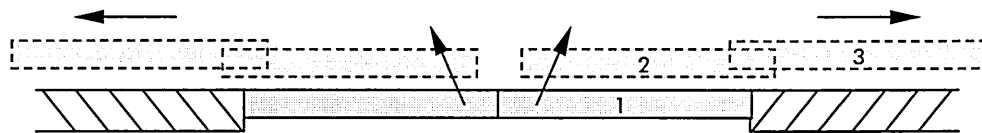


Figure 2c: Diagram showing a typical sliding plug door opening cycle

This powered door configuration requires the most complex mechanical arrangement to ensure that the doors unplug smoothly, often using guides and linkages to restrict the door leaf degrees of freedom. The two different stages of door motion (unplugging and sliding) are not easily generated using a single linear pneumatic actuator, however a rotary pneumatic actuator, or more commonly an electric motor, is a suitable power source when combined with a lead-screw mechanical transmission system. Sliding plug type powered doors have been in general use since the 1950s<sup>7</sup>. Examples of rolling stock that use this powered door configuration are:

- Northern Spirit Class 333 EMU (electric doors)
- Heathrow Express Class 332 EMU (electric doors)
- Eurostar Class 373 EMU (single leaf pneumatic doors)
- Mark 4 British Rail standard coaches (single leaf pneumatic doors)
- Virgin Voyager DMU (pneumatic doors)

### 2.5.3 Swing doors

Powered train doors featuring the swing configuration use rotary motion to generate a similar operation to sliding plug doors. Each door leaf is connected to a vertical post located just within the passenger compartment area of the train, which often doubles as a passenger support when the doors are closed. The door power source transmits rotary motion to both posts, causing them to rotate about their axis of symmetry, which in turn opens or closes the door leaves. Whilst in motion, the door leaves are kept parallel to the train body by linkages connecting each door leaf to the respective post.

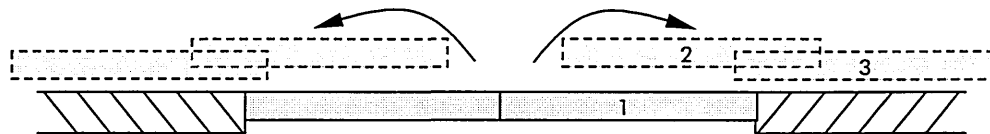


Figure 2d: Diagram showing a typical swing door opening cycle

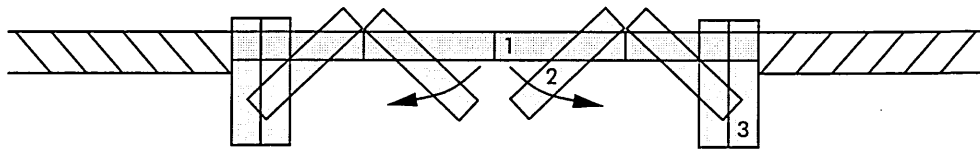
The main advantage of this configuration is in the simplicity of the rotary mechanism that generates the door motion. Additionally, the door leaves sit flush with the train body when closed, which is both aesthetically pleasing and functional, because it facilitates the sealing of the door portal against dirt and moisture ingress. A disadvantage of this configuration is that at least part of the rotating post and support frame assembly must be located within the passenger area of the train. This could lead to passenger injury and it is necessary to carefully consider the extra safety implications when designing and testing this type of door. Swing type powered doors have been in general use since the early 1960s, though they tend to be mainly used in light rail vehicle applications<sup>7</sup>. Examples of rolling stock that use this powered door configuration are:

- Sheffield Supertram EMU (pneumatic doors)
- Birmingham tram EMU (electric doors)
- Class 158 DMU (pneumatic doors)
- Class 220, 221 'Voyager' DMU (single leaf pneumatic doors)



### 2.5.4 Folding doors

The folding powered train door configuration is characterised by door leaves that fold inwards during opening and are commonly used on road bus powered doors. Their use is limited to a number of classes of train that were based upon standard road buses, such as Class 142, 143, 144. This configuration comprises two door leaves, each featuring two separate sections that are hinged in the middle. This allows the door leaves to fold as the doors open and close.



*Figure 2e: Diagram showing a typical folding door opening cycle*

Folding powered doors are not particularly suitable for high speed train services, since it is particularly difficult to seal the doors against the weather and, consequently they also have poor resistance to pressure pulse disturbances<sup>7</sup>. Examples of rolling stock that use this powered door configuration are:

- Class 142, 143, 144 DMU (pneumatic doors)

### 3. Railway industry condition monitoring

Condition monitoring is not a new concept to the UK rail industry. A wide range of condition monitoring applications has been developed and successfully implemented to address particular engineering problems. The aim of railway based condition monitoring applications is identical to those in other industries, namely to identify faults with systems or components before a critical or catastrophic failure occurs. This is particularly important in the railway industry, where the catastrophic failure of a locomotive can cause major network disruption or where the failure of an individual component could result in damage to a larger, higher-value system. Examples of current rail industry condition monitoring applications include:

- Traction-based (e.g. diesel engine or gearbox oil, traction motor monitoring<sup>8</sup>)
- Rolling stock (e.g. brake pad wear, wheel profile monitoring)
- Power collection (e.g. pantograph<sup>9,10</sup> or overhead line monitoring)
- Track (e.g. track geometry, rail profile, gauging monitoring)
- Infrastructure equipment (e.g. point motors / heaters, flange lubricator monitoring)

Prior to privatisation, British Rail Research was heavily involved with the development of railway condition monitoring applications, such as DEMON, Padview, Panchex, TRACS or Headline, for example<sup>11</sup>. Many new-build or modern trains are fitted with monitoring systems, aimed at providing comprehensive information about train sub-system performance. Nesbitt<sup>12</sup> identifies the type of monitoring systems fitted to new-build trains in the UK as well as a range of train systems that could benefit from condition monitoring, including braking systems, heating and air conditioning, engines, auxiliaries and passenger door systems.

Current research in the field of rail-related condition monitoring is also much in evidence through the Advanced Railway Research Centre at the University of Sheffield and the Rail Systems Engineering group at the University of Birmingham. A review of journals and publications also reveals that railway focussed research continues to be undertaken through a number of institutions on a range of topics, including locomotive traction motors<sup>8</sup>, single-throw mechanical equipment<sup>13</sup>, generic fault detection and isolation<sup>14</sup>, condition related maintenance<sup>15</sup> or remote diagnosis and monitoring<sup>16</sup>.

Fararooy<sup>13,17, 18</sup>, Allan<sup>18</sup> and Lehasab<sup>13,17,19</sup> have conducted research specifically relating to single-throw mechanical equipment, which includes powered train doors. Their research focussed on the condition monitoring of pneumatically powered passenger train doors, however their research is predominantly laboratory based. The condition monitoring solution developed is a complex, continuous system designed to be installed within a train on a per-door basis. However, retrofitting even low value equipment to a fleet of train doors is not currently financially viable, and so the system is presumably limited to new build fleets of trains.

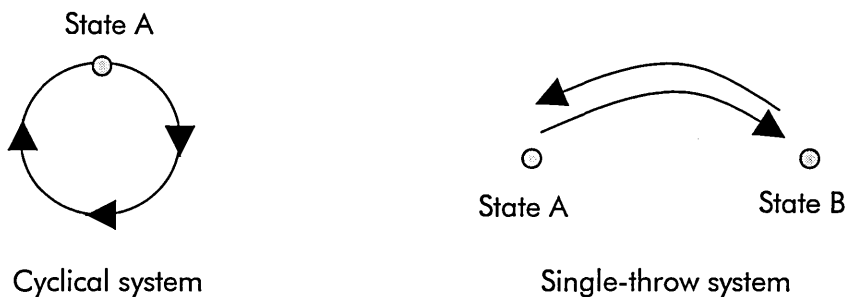
Dassanayake<sup>20</sup> has recently completed research at the University of Birmingham concerning pneumatic powered train passenger doors, sponsored by Vapor UK, the UK branch of the Canadian door manufacturer. The research addressed the continuous on-line monitoring of pneumatic sliding train doors using a variety of different transducers installed on a per-door basis. The performance of each door was analysed and classified using a range of advanced analysis techniques, including neural networks for fault identification and classification<sup>21</sup>.

This thesis discusses the development of a prototype condition monitoring tool for powered train doors that does not require any retro-fitting of equipment to door systems. The condition monitoring detailed in this thesis is non-continuous or off-line and would be undertaken at train maintenance depots. This implementation will allow the condition monitoring tool to be used both on existing passenger doors and new build door systems. To further extend the applications, the data analysis routines could be incorporated into new build fleets as part of the door control systems. No previous research relating to this particular aspect of condition monitoring was identified.

#### 4. Powered train door condition monitoring

To successfully condition monitor a complex electro-mechanical system such as powered train doors, it is necessary to understand the roles and purposes of the different components. Subsequently, the component (or components) to be monitored must be identified which is most likely to provide useful data relating to the condition of the door system. The selection process also needs to consider the parameters that can be measured, the measurement technique and the frequency of the monitoring process. All of these considerations are inter-related and there may be multiple suitable condition monitoring techniques for any particular system. For powered train doors, the data generated by the selected condition monitoring technique will need to be analysed and interpreted in order to determine whether a door is operating correctly. This analysis is most effectively undertaken by a computer, which can also process and present the raw data or results as required. For this reason, transducers will be needed to measure specific parameters and generate corresponding signals to be interpreted by a datalogger. The datalogger will allow the signals from the transducer to be transferred to a personal computer (PC) and stored for further analysis or interpretation.

This section will present the different component, parameter, transducer and datalogger options that were considered for the condition monitoring of both electric and pneumatic powered train doors. The final choice of solution for pneumatic and electric powered train doors will be presented along with the reasoning behind each selection. Additionally, any specific items of equipment that were selected to implement the condition monitoring technique will be identified.



*Figure 4a: Diagrammatic representation of cyclical and single-throw systems*

Powered train doors are unlike other common electro-mechanical condition monitoring applications, because they are an example of single-throw mechanical equipment. This means that the system does not constantly repeat one specific motion, for example a rotating drive shaft. A single-throw mechanical device moves from one state to another (e.g. state A to state B) and this state transition is defined as a forward throw. Transition from state B to state A is defined as a reverse throw<sup>19</sup>. This second motion is normally simply the reverse of the first motion (figure 4a). It should therefore be possible to determine the condition of the powered door system by observing and analysing aspects of the door performance during the opening and closing cycles.

#### 4.1 Monitoring pneumatic doors

Figure 4b identifies the components that could form the basis of a performance monitoring solution for pneumatic powered train doors. For each selected door component, one or more potential parameters are identified, along with a suitable unit of measurement, a typical transducer and contributory factors such as the cost, difficulty or reliability of implementing the condition monitoring solution.

Component	Parameter	Units	Transducer	Difficulty <sup>1</sup>	Cost <sup>1</sup>	Reliability <sup>2</sup>	Retrofit <sup>3</sup>
Pneumatic actuator	Pressure	Bar	Pressure	2	2	3	Maybe
	Air flow	ls <sup>-1</sup>	Flowmeter	5	5	1	Yes
	Vibration	mms <sup>-2</sup>	Accelerometer	5	3	4	Yes
Door leaf	Displacement	mm	Draw-wire	3	2	1	Maybe
	Velocity	mms <sup>-1</sup>	Draw-wire	3	2	1	Maybe
	Acceleration	mms <sup>-2</sup>	Draw-wire	3	2	1	Maybe
Mechanical lock	Displacement	mm	Linear motion	5	3	2	Yes
Traction interlock	Current	mA	Current probe	1	2	1	No

Figure 4b: Potential performance monitoring solutions for pneumatic train doors

<sup>1</sup> Difficulty / cost of measurement, data collection and analysis (1 - low, 5 - high)

<sup>2</sup> Reliability of measurement, data collection and analysis (1 - high, 5 - low)

<sup>3</sup> is modification / retrofitting required to take reliable measurements? (Yes / Maybe / No)

This review of the condition monitoring options for pneumatic powered train doors formed the basis of the project. Based upon this assessment, three different parameters were chosen as those most likely to lead to a successful condition monitoring solution within the project constraints. The selected parameters are:

- Pneumatic actuator air pressure during door opening and closing cycles;
- Door leaf displacement during opening and closing cycles;
- Traction interlock circuit status during opening and closing cycles.

These three parameters are most likely to be sensitive to incorrect door set-up, component failure or other likely causes of door unreliability. The actuator cylinder air pressure will provide useful information about door operation<sup>12</sup> as well as the door operating forces, whilst the door leaf displacement will define the resulting output of the power source, including derived velocities and accelerations. The status of the traction interlock should provide insight into a common source of train unreliability, namely failure or incorrect setting of microswitches linked to the traction interlock circuit. All of these parameters can also theoretically be measured using relatively cheap transducers without requiring modification to existing train systems.

The other parameters in the table were not deemed suitable as potential condition monitoring solutions for pneumatic powered train doors. The main factors behind this decision were:

- The parameter would not provide useful information concerning the door condition or performance (e.g. pneumatic actuator vibration);
- The parameter would be too difficult, expensive or unreliable to measure;
- The measurement method would require modification to train systems, or would require tailoring to different types of train door.

## 4.2 Monitoring electric doors

Figure 4c identifies the components that could form the basis of a performance monitoring solution for electric powered train doors. For each selected door component, one or more potential parameters are identified, along with a suitable

unit of measurement, a typical transducer and contributory factors, such as the cost, difficulty or reliability of implementing the condition monitoring solution.

Component	Parameter	Units	Transducer	Difficulty <sup>1</sup>	Cost <sup>1</sup>	Reliability <sup>2</sup>	Retrofit <sup>3</sup>
Motor	Current	mA d.c.	Current probe	1	2	1	No
	Temperature	°C	IR camera	1	5	4	No
	Shaft rotation	°	Rotary encoder	5	3	2	Maybe
	Vibration	mms <sup>-2</sup>	Accelerometer	5	3	4	Yes
Door leaf	Displacement	mm	Draw-wire	3	2	1	Maybe
	Velocity	mms <sup>-1</sup>	Draw-wire	3	2	1	Maybe
	Acceleration	mms <sup>-2</sup>	Draw-wire	3	2	1	Maybe
Mechanical lock	Displacement	mm	Linear motion	5	3	2	Yes
Traction interlock	Current	mA d.c.	Current probe	2	2	2	No
Transmission	Vibration	mms <sup>-2</sup>	Accelerometer	5	3	4	Yes

*Table 4c: Potential performance monitoring solutions for electric train doors*

This review of the different condition monitoring options for electric powered train doors formed the basis of the project. Based upon this assessment, three different parameters were chosen as those most likely to lead to a successful condition monitoring solution within the project constraints. The selected parameters are:

- Door motor electrical current during opening and closing cycles;
- Door leaf displacement during opening and closing cycles;
- Traction interlock circuit status during opening and closing cycles.

These three parameters are most likely to be sensitive to incorrect door set-up, component failure or other likely causes of door unreliability. The motor current will provide useful information about the load on the door motor (forces to operate the door), because the torque is proportional to the electrical current<sup>22</sup>. The displacement of the door leaf will define the resulting output of the power source, including derived velocities and accelerations. The status of the traction interlock

<sup>1</sup> Difficulty / cost of measurement, data collection and analysis (1 - low, 5 - high)

<sup>2</sup> Reliability of measurement, data collection and analysis (1 - high, 5 - low)

<sup>3</sup> Is modification / retrofitting required to take reliable measurements? (Yes / Maybe / No)

should provide insight into a common source of train unreliability, namely failure or incorrect setting of microswitches linked to the traction interlock circuit. All of these parameters can also theoretically be measured non-intrusively using relatively cheap transducers without requiring modification to existing train systems. In figure 4c, the traction interlock parameter was given slightly higher scores than the motor current parameter, even though it utilises exactly the same technique. This is because the traction interlock signal current will probably be two orders of magnitude smaller than the applied motor current (e.g. 25 mA compared to 2500 mA) and consequently more difficult to measure.

The other parameters in the table were not deemed suitable as a potential condition monitoring solution for electric powered doors. The main factors behind this decision were identical to those highlighted for pneumatic doors, namely that the:

- Parameter would not provide useful information concerning the door performance (e.g. temperature of door motor).
- Parameter would be too difficult, expensive or unreliable to measure.
- Measurement method would require modification to train systems, or would require tailoring to different type of train door.



## 5. Initial data collection

Three critical phases in the development of a viable condition monitoring technique are:

1. Analysis of the system that is being monitored, both theoretically and practically;
2. Testing of the data collection process;
3. Collection of sample data.

These phases are important because without an understanding of the target system, it will be difficult to analyse and understand the data that is generated by the condition monitoring process. Analysis of the system will allow the likely failure modes to be determined, assuming they are not already known, and provide insight into the manner in which each failure mode can be identified through the condition monitoring data. Basic testing of the transducers in the operating environment of the condition monitoring system is also vital to allow early identification of operational or technical problems. This forms an integral part of the final data collection phase, which provides preliminary data upon which the condition monitoring process will be based.

This thesis is concerned with the development of a generic condition monitoring technique that can be applied to a wide range of pneumatic and electric powered passenger train doors. For this reason, an initial theoretical analysis of a powered train door was discounted, since any mathematical model representing a specific type of door would not be valid for different powered train doors. Another reason to discount the theoretical analysis and modelling of powered train doors was simply due to the complexity of the system. A mathematical model probably could have been developed, however the results would have required extensive verification and calibration through comparison with practical data. In order for any model to be sufficiently accurate to use as a benchmark for a condition monitoring technique, it would need to be highly detailed, which would probably result in a non-generic solution that could not simply be modified for use on different powered train door systems.

Consequently, it was decided that an intense period of data collection at a range of train maintenance depots on a variety of trains would be a suitable approach for generating useful door operating data, upon which to base the development of a condition monitoring solution for powered train doors. This section of the thesis provides basic

information about the transducers that were selected for this purpose. It will also detail the main findings and outcomes of the intensive data collection period.

## 5.1 Data collection

A basic piece of equipment that is required to collect and store data from any type of transducer is a datalogger. Dataloggers convert voltages or currents generated by transducers into a format that can be stored and understood by computers. This is normally achieved through the use of an analogue to digital converter (ADC), which digitises the input signal into a number of discrete numerical values. Prior to selecting a suitable datalogger for data collection in train maintenance depots, the following requirements were identified:

- Multiple input channels would be required because the anticipated number of input parameters was thought in the range 2 to 4.
- The resolution of the ADC should be at least 8 bit. Higher resolutions would be preferable to improve the resolution of even small signals, improve the accuracy of the conversion and maximise equipment flexibility.
- A minimum sampling frequency of 10 samples per second per channel (10 Hz) would be needed in order to capture data. A higher sample rate would be preferable, though it was envisaged that 100 Hz would be a practical maximum frequency, given that high frequency vibration or acoustic emission condition monitoring techniques had not been selected.
- It must be possible and practicable to transfer, view and analyse data from the datalogger on a standard PC.
- The datalogger must be suitable for use in train depot environments and relatively inexpensive to meet the project budgets.

A suitable datalogger was identified and purchased which fulfilled all of these requirements (see appendix A for further details of the datalogger). The datalogger was used throughout the project as a simple means of testing transducers and signal conditioning modules, developing data collection processes and collecting data.

## 5.2 Collection of pneumatic door performance data

Once the parameters had been selected for pneumatic powered train doors, it was necessary to identify and procure suitable transducers that would complete the test condition monitoring system for pneumatic train doors. The problem of measuring the door motion during opening and closing cycles can be solved in a variety of ways. A draw-wire transducer connected to a door leaf was chosen due to the simplicity of the solution and it consists of a length of spring-loaded cable attached to a potentiometer. SHU was able to provide a draw-wire transducer with a cable length of 2 meters, making it ideal for the application (see appendix A). An output voltage is generated in proportion to the cable extension, which allows the door displacement to be measured using the datalogger (velocity and acceleration can be derived from the displacement by differentiation).

Pressure transducers generate an output signal proportional to the sensed pressure. Train air systems operate at a nominal maximum pressure of between 7 bar and 8 bar, which defines the upper sensing limit for a suitable transducer. In practice however, a system such as passenger doors operates at a lower, regulated pressure of approximately 5 bar. A Druck pressure transducer was selected to complete the test condition monitoring system for pneumatic train doors (see appendix A).

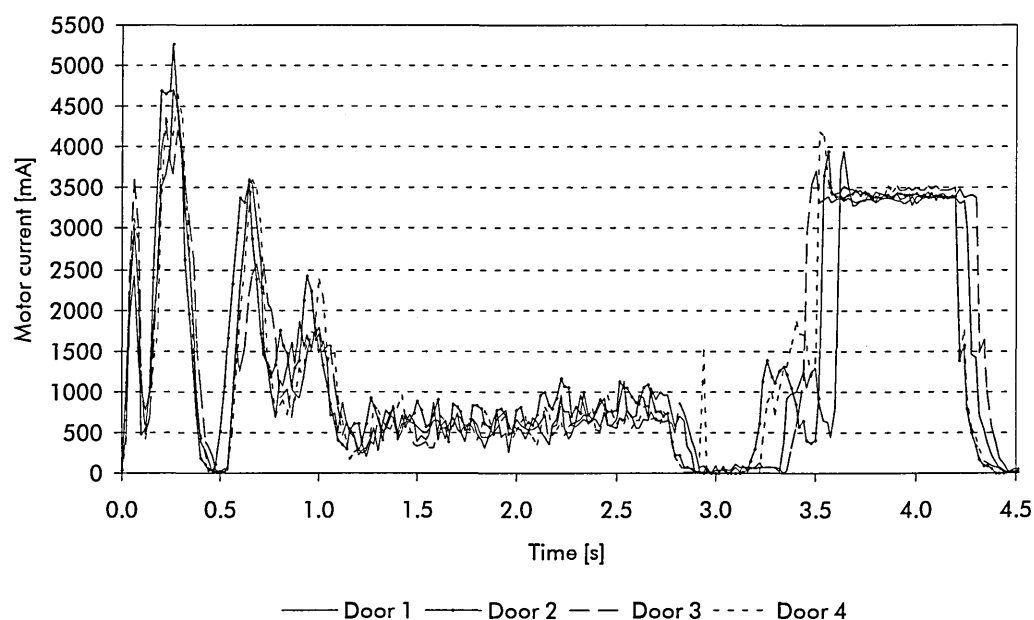
## 5.3 Collection of electric door performance data

The draw-wire transducer was also used to generate door displacement, velocity and acceleration data for electric powered train doors (see appendix A for further information about this transducer). In section 4.2 the most suitable method for measuring the applied motor current during door opening and closing cycles was identified as a Hall effect current probe. Current probes are able to measure a wide range of a.c. and d.c. currents (different probes are required for a.c. or d.c. applications) with isolation<sup>23</sup>, which means no direct contact with the electrical circuit. This isolation is advantageous in circumstances where safety is critical, which is definitely true in railway applications. Drafts<sup>22</sup> gives a detailed description of Hall effect current probes.

The LEM-HEME PR30 was identified as the most suitable current probe for the door motor application, because it is a clamp-on current probe suitable for measuring low currents. This means that the coil can be broken through operation of a lever allowing it to be placed around a wire in-situ and allows measurements to be taken without modification to train door systems (further transducer details are given in appendix A). This transducer was also the most suitable current probe for measuring the traction interlock current, even though typical traction interlock currents are two orders of magnitude smaller than door motor currents.

#### 5.4 Shift of project focus onto purely electric powered doors

Towards the end of the intensive data collection period (end of the first year of the two year project), it was clear that electric powered train doors offered a uniform and consistent motor current characteristic during opening and closing cycles (see figure 5a).



*Figure 5a: Graph highlighting the typical consistency of door motor current characteristics (figure shows four different door opening cycles on a modern EMU)*

The motor current data enables specific aspects of door motion to be identified, as detailed below:

- door unlocks during the first 0.5 s of data operation (high motor torque);
- door leaves are unplugged between 0.5 s and 1.25 s (high motor torque);
- door leaves slide open between 1.25 s and 3 s (constant, low motor torque);
- door leaves decelerate and are fully open at 3.5 s (motor stalled).

Continuous review and analysis of the raw data collected from the trains identified the door motor current characteristic to be the most appropriate basis for an electric powered train door condition monitoring technique. This is because the clamp-on current probes were quick and simple to use and provided consistent information about the door performance via the motor current. In comparison, measuring door leaf displacement was cumbersome, slow, prone to measurement inaccuracy and generally impractical for use in a train depot environment. Although the door displacement data did provide valuable information relating to door motion, the velocity and acceleration data was not reliably repeatable and the marginal increase in information was greatly outweighed by time, physical and computational disadvantages.

After extensive data collection and analysis it was also obvious that a similar condition monitoring solution, based upon the door actuator pressure characteristic, for pneumatic powered train doors would not be successful. The following factors all contributed to this conclusion:

- Measurement of the door cylinder air pressure can only be undertaken using in-built test points in each vehicle<sup>5</sup>. Different fleets of train use different types of test points, which require adapters in order to interface with a standard pressure transducer.
- The test point is not necessarily near to the door under investigation and consequently the observed pressure changes are not only related to door operation. In worst-case scenarios the test point was also near to an air reservoir, which if sufficiently well supplied, is able to maintain a near constant pressure at the point of measurement. Thus flow measurement would be more appropriate in principle, however for this application it would be impractical.

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<sup>5</sup> no modification to train systems is permitted.

- Compressed air is also used for other train systems, such as braking, pantograph operation or indeed other doors on the train. For this reason, measured pressure changes during door operation can be easily influenced by the other systems as well as by compressor efficiency or duty cycle.

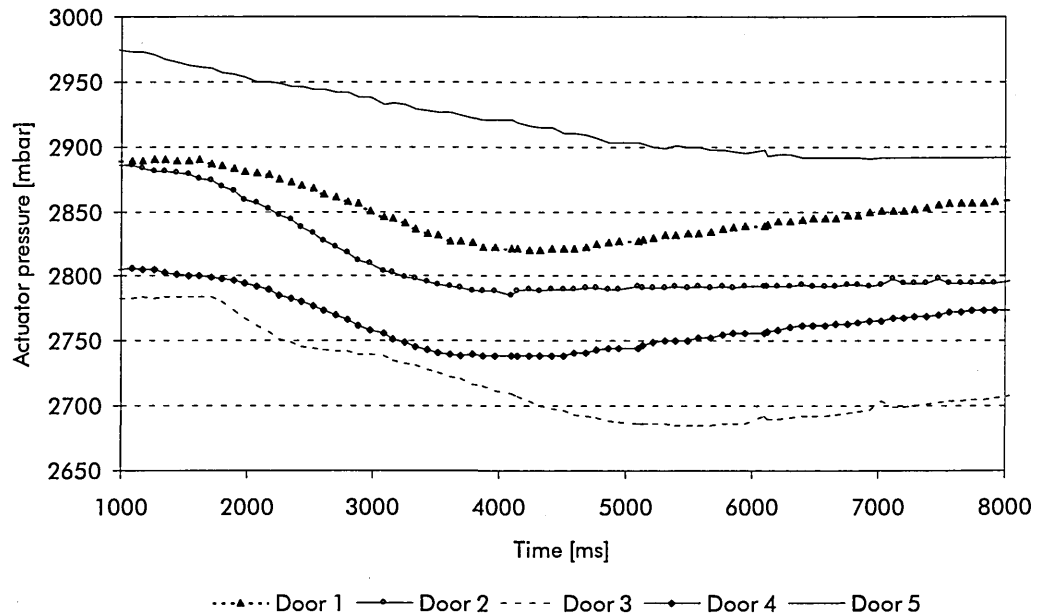


Figure 5b: Example of pneumatic door characteristic variability between doors

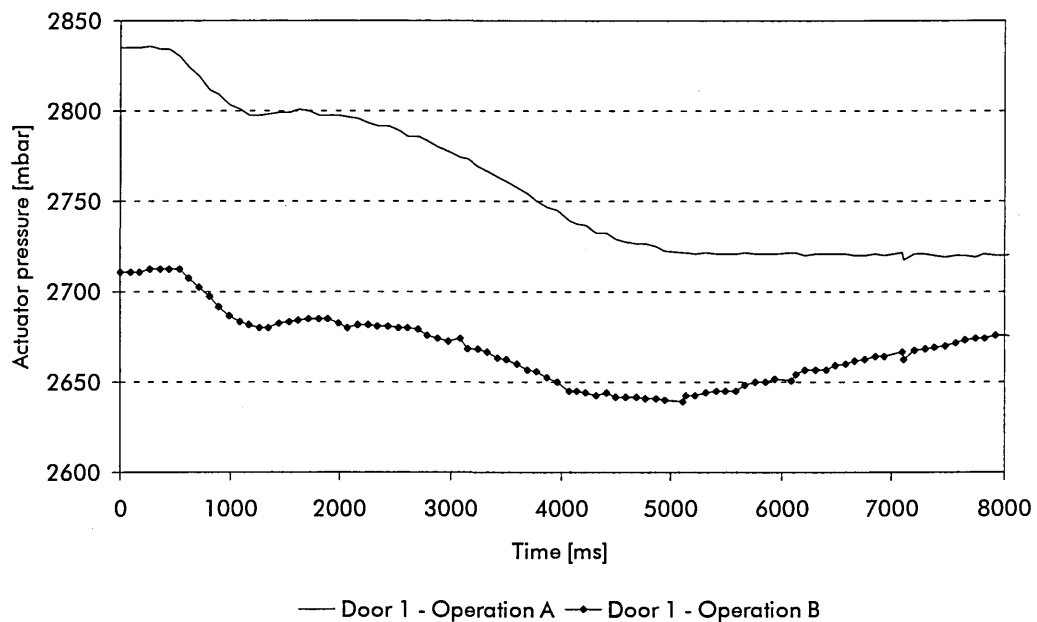


Figure 5c: Example of pneumatic door characteristic variability for one door

Consequently, the raw data readily available within the project constraints did not appear to be particularly consistent, repeatable or reliable. Figure 5b shows example pressure characteristics collected from different doors on one train and figure 5c shows pressure characteristics recorded sequentially from only one pneumatic train door. These graphs highlight the inconsistency and lack of clearly definable features of a pneumatic actuator operating characteristic for different doors as well as for sequential operations of a single door. On the basis of these observations, the decision was made to redefine the scope of the TCS project to focus purely on electric powered train doors. This decision will consequently be mirrored by this thesis.

### 5.5 Selection of final condition monitoring parameters

The intensive period of door performance data collection and analysis fulfilled the intended purpose, because it allowed the identification of two suitable parameters that could form the basis of a viable condition monitoring technique for electric powered passenger train doors. The two final selected parameters are:

1. Door motor current drawn during the opening and closing cycles of a door.
2. Traction interlock status, specifically the time at which it changes state.

Both parameters will be measured using clamp-on current probes identified previously, because they are an ideal solution to the problem of measuring electric currents without invasive electrical connection to train circuits. They have the additional advantage of being suitable for all types of electric train door systems. This is important, because it means that the condition monitoring solution will not require any safety approval prior to use on a train and the same transducers can be used independently of the class of train. The motor current is an ideal basis for a condition monitoring system due to the consistent operation of electric door systems. This applies both to successive measurements taken at an individual door and to measurements taken from different doors within a fleet (see figure 5a).

The current drawn by the door motor during opening and closing cycles will be complemented by information provided by the second current clamp relating to the status of the traction interlock system. The traction interlock circuit is an

important safety system that ensures that the train brakes will be applied automatically if a door is open in traffic. If a door is also not correctly closed and locked at a station, the driver will be unable to take tractive power. The traction interlock circuit is a common source of train delay that often generates many "no fault is found" problems. Therefore, data relating to the status of the traction interlock circuit will provide engineers with more information about faulty doors.

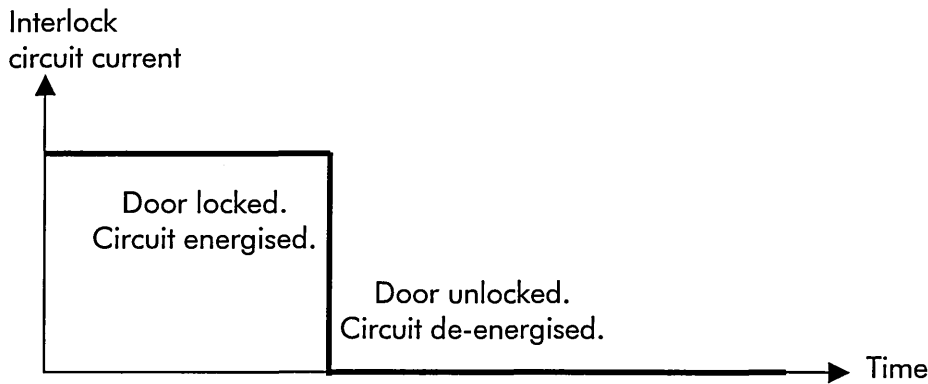


Figure 5d: Idealised representation of traction interlock circuit operation

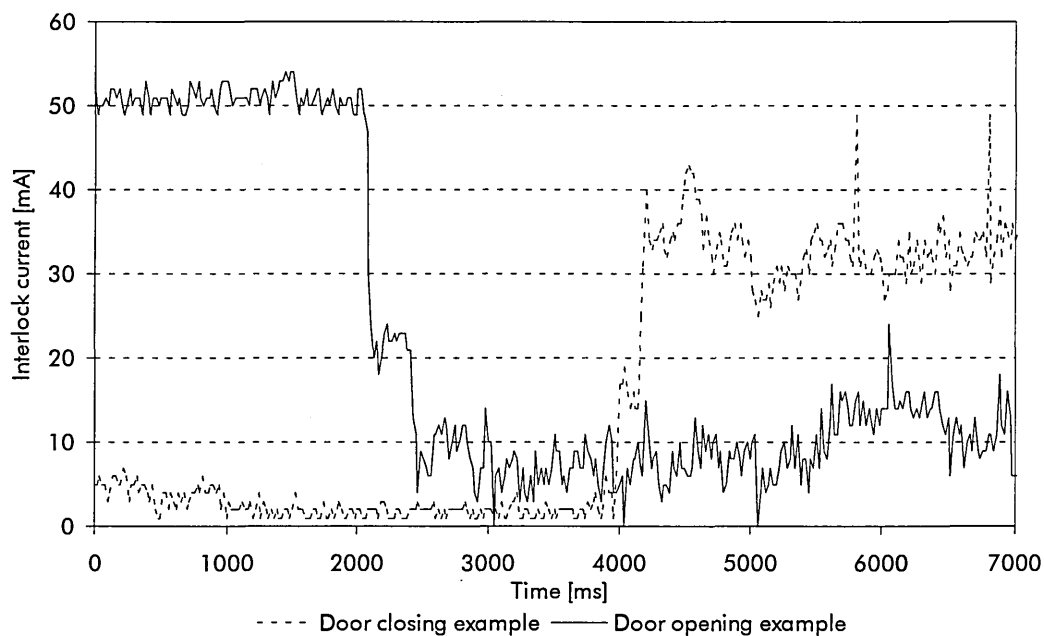


Figure 5e: Examples of monitored traction interlock status changes

Relays are used to identify when traction interlock is gained or lost. For this reason the signal is either in a low (no current) or a high (some current) state and the change in signal between these states should be an almost perfect step change (see figure 5d). However unlike semiconductor technology, which detects rising or



falling edges of the signal, the relays used to detect traction interlock status operate only when the current reaches a specified magnitude. This can be considered to be essentially a design feature that helps to ensure reliable operation, because a stable, clean and interference free power supply is generally not available to train electrical systems. However, this makes the reliable detection of the traction interlock status change particularly difficult (see figure 5e).

## 5.6 Examples of real door faults

During the period of data collection, a number of door motor characteristics from a range of train fleets were observed to deviate from the standard motor characteristic, implying a potential door fault. This section of the thesis will present the normal and abnormal door characteristics graphically, discuss the differences and, where possible, suggest a reason for the fault.



Figure 5f: Example faulty door motor characteristic 1

Figure 5f shows a faulty door opening cycle for a modern airport link EMU. The motor current is significantly higher and the time taken to open the door fully is also shorter, at 2.0 seconds compared to the normal 2.5 seconds (the high current at the end of the data represent a stalled motor trying to open a door that is

already fully open). It is possible that incorrect or faulty door control software is responsible for this door response. High motor current consumption normally implies mechanical stiffness or high friction, however in this case, the faster door opening speed appears to contradict this possible explanation. The closing performance of the same door is presented in figure 5g, which shows that the door takes roughly 1 second longer to close than normal. The abnormal door motor current data does also not match the normal motor characteristic at all, supporting the hypothesis that faulty control software is the cause of the door problems.

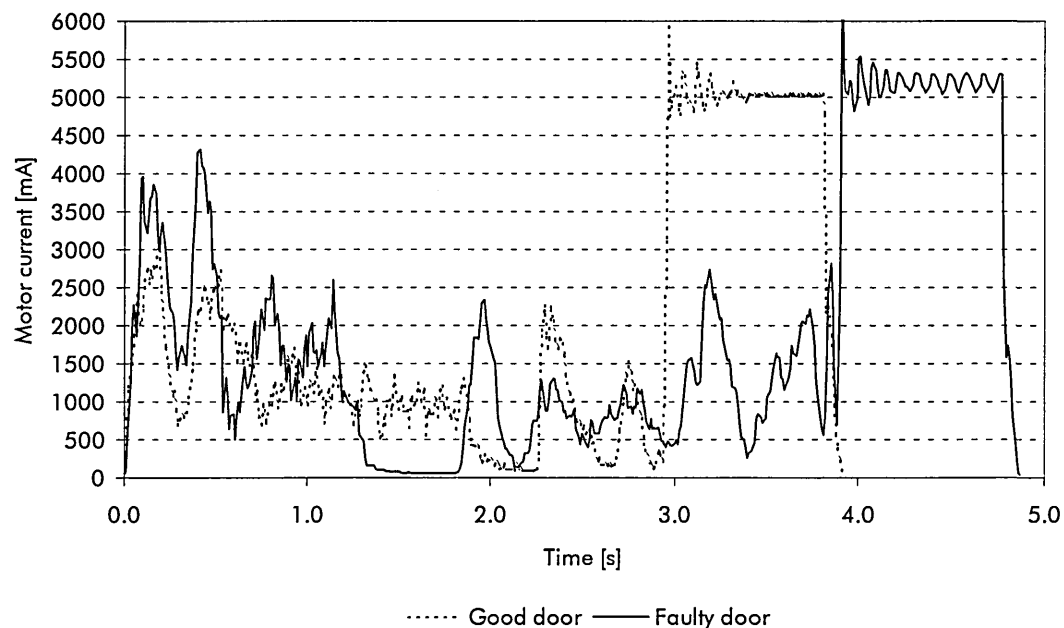


Figure 5g: Example faulty door motor characteristic 2

The door closing motor cycle for a new EMU, designed for suburban services, is shown by figure 5h. Increased peak motor current is identifiable as the door leaves plug flush with the vehicle body at roughly 3.5 seconds (the door plugging motion occurs between roughly 2.5 and 3.75 seconds). This could signify the beginnings of a problem relating to mechanical stiffness in the plugging mechanism. Sliding plug doors often suffer from mechanical problems in this region, because the mechanism has to force the doors through a defined curved path. Incorrect set-up, misalignment or dirt build-up can all cause increased mechanical stiffness, resulting in increased motor torque, and hence current.



Figure 5h: Example faulty door motor characteristic 3

Another door motor closing characteristic from the same fleet shows the result of an incorrectly set-up microswitch (figure 5i). In this example the stalled door motor is not turned off once the doors are closed (4.5 seconds), which, if undetected, could have eventually resulted in motor burn-out. The fault was easily rectified by re-positioning the microswitch so that the closing doors cause the motor to be deactivated.

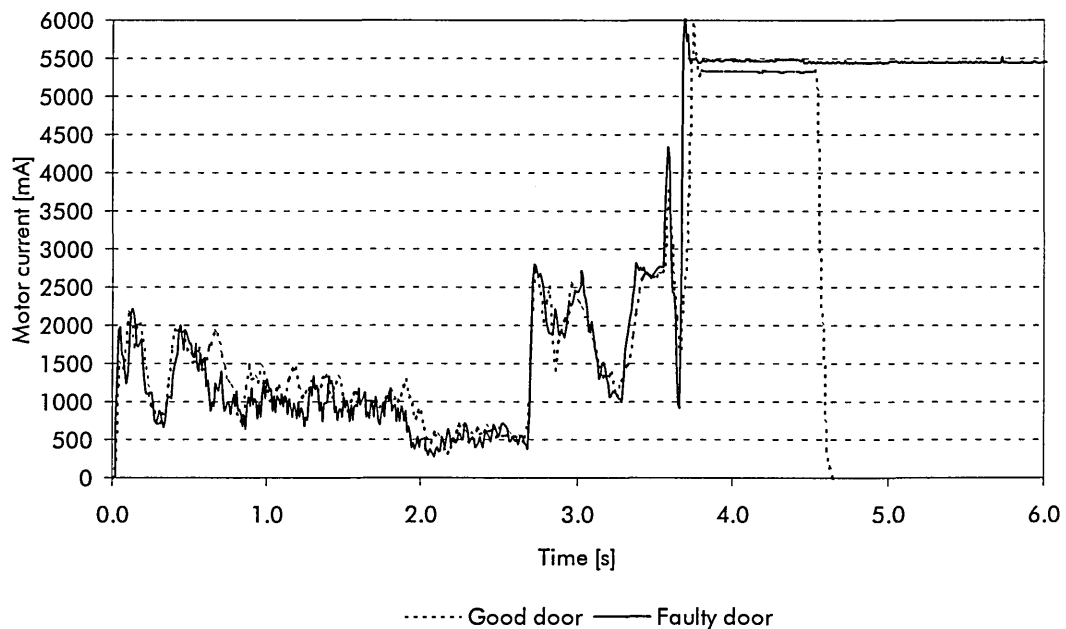


Figure 5i: Example faulty door motor characteristic 4

A light-rail vehicle swing plug door opening characteristic is presented in figure 5j. The doors initially open quickly and are approximately two thirds open after two seconds. The door motion is damped during the last third of motion (good door) until the leaves are fully open at 3.5 seconds. This fleet suffered from excessive dirt build-up in the door mechanism due to poor design, making the system stiff and difficult to operate. The motor must therefore apply higher torque, represented by the high current values and slower door motion between 2.0 and 4.5 seconds.

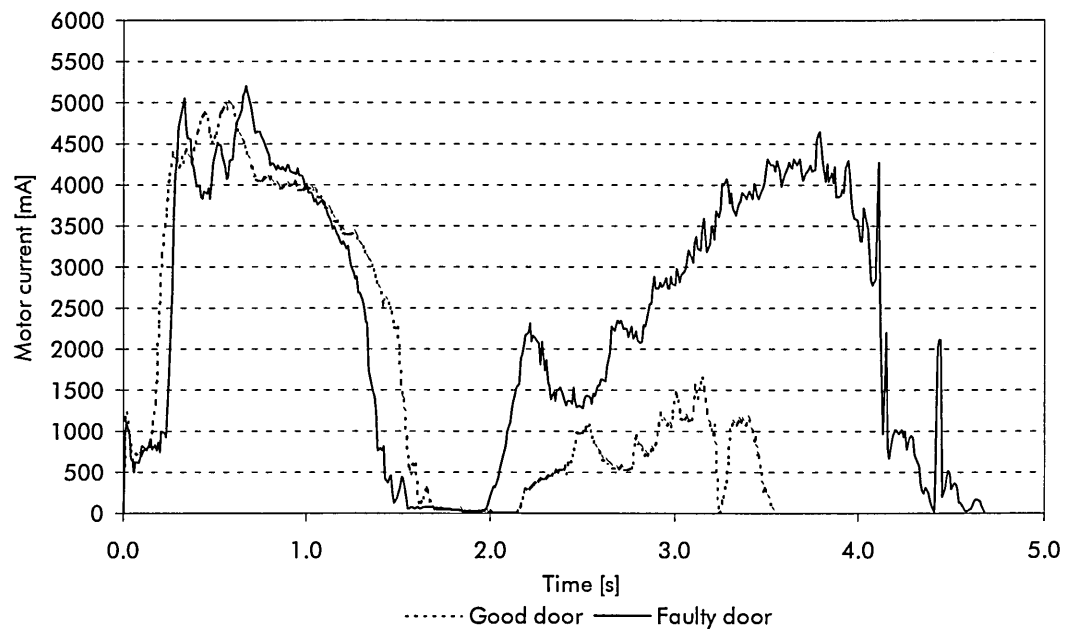


Figure 5j: Example faulty door motor characteristic 5

A door closing cycle for the same light-rail fleet is shown by figure 5k. In this example, the door takes 1 second longer to close than normal. The data shows that the door is slow throughout the entire closing cycle, rather than at any specific point. However, it is interesting to note that the faulty motor current data is broadly similar in magnitude to the good door motor data.

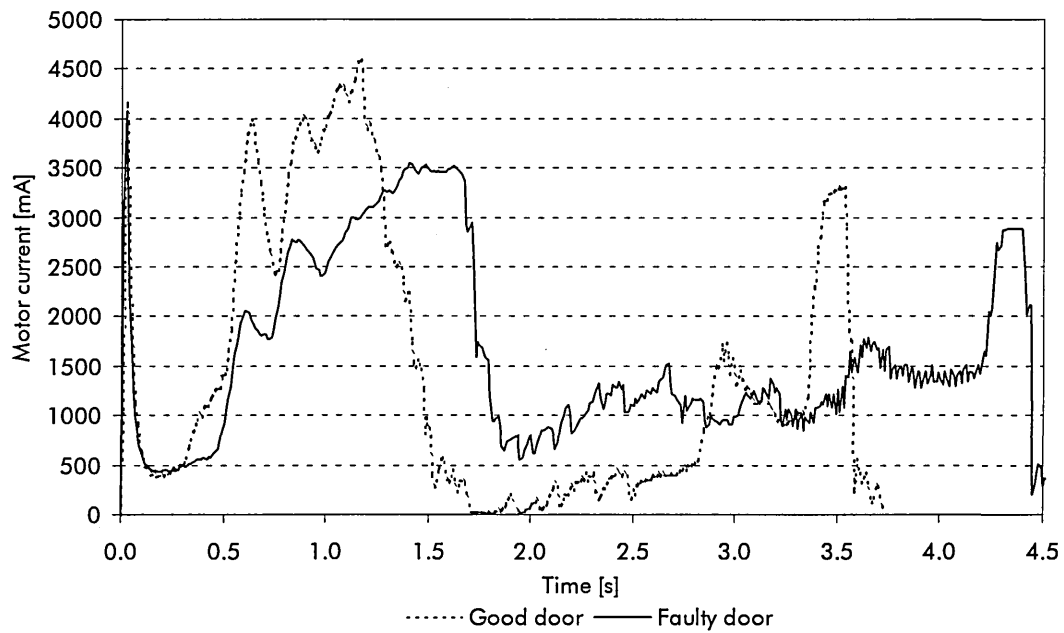


Figure 5k: Example faulty door motor characteristic 6

These six examples show the types of abnormal door operation that were observed on a range of different fleets. For all of the cases, it is possible to identify potential causes of the observed problems, which would enable a train maintenance team to determine the root cause more quickly than by visual inspection and enable a solution to be defined. As knowledge and experience relating to door faults is gained, common patterns and relationships can be established, enabling door faults to be reliably identified in their early stages.

## 6. Data analysis techniques

This chapter of the thesis will present the data analysis techniques that were investigated during the development of a suitable condition monitoring solution for electric powered train doors. The potential implementation, advantages, disadvantages and suitability of each technique will be outlined. However, the detailed theory relating to each technique will not be discussed, except where specifically relevant. The analysis techniques discussed here do not form an exhaustive list of those reviewed, but are merely of most interest. The raw data available to each analytical method is of course identical and comprises:

1. Door motor current data (either door opening or door closing) [mA]
2. Traction interlock current data [mA]

A major problem, in developing a suitable analysis technique, related to collecting fault data from incorrectly operating powered train doors. Faults could not be introduced into the rolling stock at depots due to the safety implications and obvious operational constraints. Also, the project did not have the financial capability to invest in a powered door test rig. For these reasons, the analysis techniques could only be reviewed and developed based upon data relating to a small number of faulty doors.

### 6.1 Parametrical analysis

Parametrical analysis was considered as a first step to developing a suitable data analysis technique. Parametrical analysis potentially allows large amounts of data to be represented by a small number of parameters that can be analysed for trends or patterns. The following parameters were considered because they are simple to calculate and easy to interpret in relation to powered train door systems:

- Maximum motor current [mA]
- Minimum motor current [mA]
- Mean motor current [mA]
- Median motor current [mA]
- Sum of all sampled motor current values [mA]
- Total motor operating time [ms]

- Interlock operation as a proportion of the total motor operating time [%]

In order to develop a successful condition monitoring technique based upon statistical analysis, it must be possible to differentiate the parameters of faulty doors from normal doors. If this cannot be achieved, then the technique is not suitable, or requires modification. A major factor in the success of such a technique is the selection of parameters. The parameters described above represent very simple, physical parameters of the system under investigation, however there are many other parameters that could be considered, for example:

- Standard deviation of the motor current data from the mean
- Variance of the motor current data
- Power consumed by the motor (integral of current squared)

Data were collected from a number of train doors that were considered to be operating incorrectly and this incorrect operation was identifiable by the human eye through visual inspection of the door motor current data. Therefore it was decided to concentrate on parameters that described the physical features of the door motor data in the time domain. Frequency domain analysis of the door motor data was investigated. However, based upon the limited data available, no distinction was identifiable between normal and abnormal door operation.

The following conclusions, or observations, were identified based upon this investigation into the suitability of the parametrical data analysis:

1. No single parameter was able to reliably differentiate between normal or abnormal doors. This was primarily due to the wide numerical range of the motor current data, which, when converted into a small number of parameters, ensured that all of the detail within the data was lost. This shortcoming could be overcome through the generation of more parameters or the segregation of similar data.
2. It was possible to identify faulty doors by reviewing the changes in combinations of two or three different parameters, though this was not particularly reliable.
3. Calculating the minimum motor current parameter did not add value to the analysis, since this value was observed to be always zero, or very close to zero.

4. All of the parameters could be form the basis of a historical trend analysis. Since all doors within a fleet should operate identically, it should be possible to quickly assemble a large database of trends for each parameter. The change in each parameter value for all doors within a fleet of trains could be used to identify potential future faults prior to in-service failure.

In summary, parametrical analysis alone is unlikely to be suitable for condition monitoring applications, since it appears to be unable to easily differentiate between faulty and normal train door operation. The technique could however be used as the basis for a long-term trend analysis. A parametrical analysis could be improved through the use of a greater range of parameters or data processing.

## 6.2 Error detection

Another possible analysis technique that was identified and subsequently tested was error detection, or pattern matching. Both types of algorithm compare data under investigation to a known set of data. A pattern matching technique would attempt to describe how well the two sets of data match, whereas an error detection routine would identify the mismatch or error between the data. Both types of analysis are totally dependent upon the availability of a known characteristic, against which to compare the data. This could be a:

- Single set of data defining the normal operation of an electric train door;
- Number of sets of data, each defining a typical failure mode.

In this application, the known characteristic always defines the door motor operating cycle under normal or correct conditions. This is primarily because the different motor characteristics corresponding to the various failure modes of the door are probably not known and it is also relatively easy to define the motor characteristic describing normal operation.



### 6.2.1 Direct data comparison

The simplest error detection routine compares two arrays of data,  $setA[10]$  and  $setB[10]$ , and generates a set of error values,  $error[10]$ , thus:

$$error_i = setA_i - setB_i \quad (Equation\ 6.1) \quad \text{where } i \text{ is the array index.}$$

When the data contained within  $setA$  is identical to that defined in  $setB$ , then  $error$  will always be zero. As data in  $setA$  deviates from the corresponding data in  $setB$ , so the error increases. This is potentially an ideal method of analysing the train door motor current to determine if a door is operating normally (low error) or if it is operating abnormally (high error). This simple analysis technique was quickly identified as unsuitable for the application of powered train door condition monitoring. Figures 6a and 6b each contain two sets of sample door operating data and highlight how, for the technique to be successful, the collected data must be perfectly synchronised to ensure an acceptable data match.

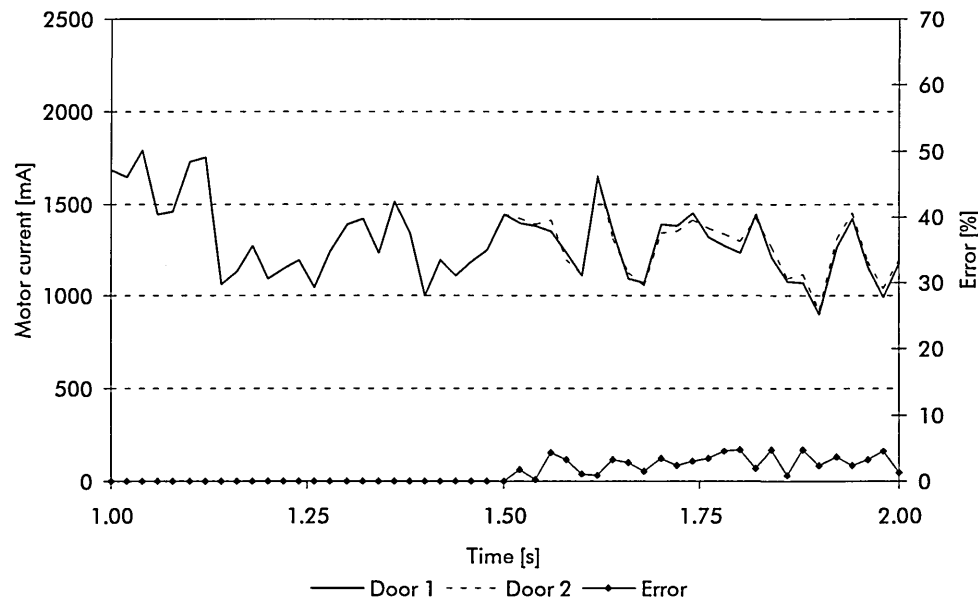


Figure 6a: Graph of synchronised motor data and corresponding error

The two sets of door motor data shown in figure 6a are nearly identical. The second set of data is identical to the first set for the first 1.5 seconds. For the subsequent 1.5 seconds, a random error factor of  $\pm 5\%$  is added to second

set of data. For this reason, figure 6a shows either zero error, or low error throughout. Figure 6b contains exactly the same two sets of data used in figure 6a. The only difference is that the second set of data has been offset from the first by 1 sample. The error detection algorithm compares each array index in turn and so, due to this offset, the calculated error is much greater.

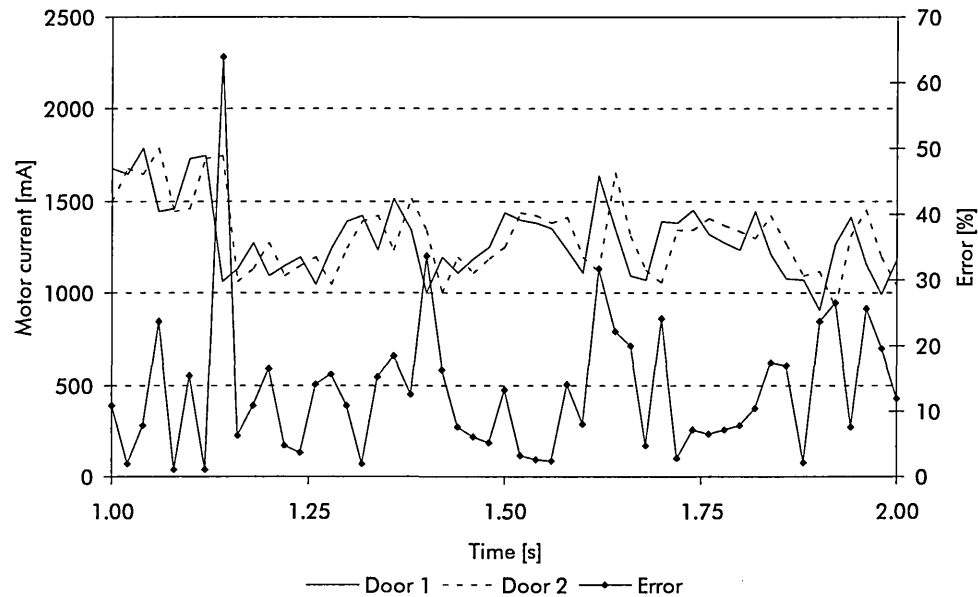


Figure 6b: Graph of unsynchronised motor data and corresponding error

However from an operational perspective, the data are identical and both should have a correspondingly low error. This highlights the unsuitability of this simple error detection algorithm for this condition monitoring application. The artificial offset introduced into the data is typical of data collected from condition monitoring systems. In fact it must be expected that different door systems respond differently on a sample by sample basis, even if the overall response can be considered identical. For this type of algorithm to be suitable the algorithm must be modified. Possible modifications are:

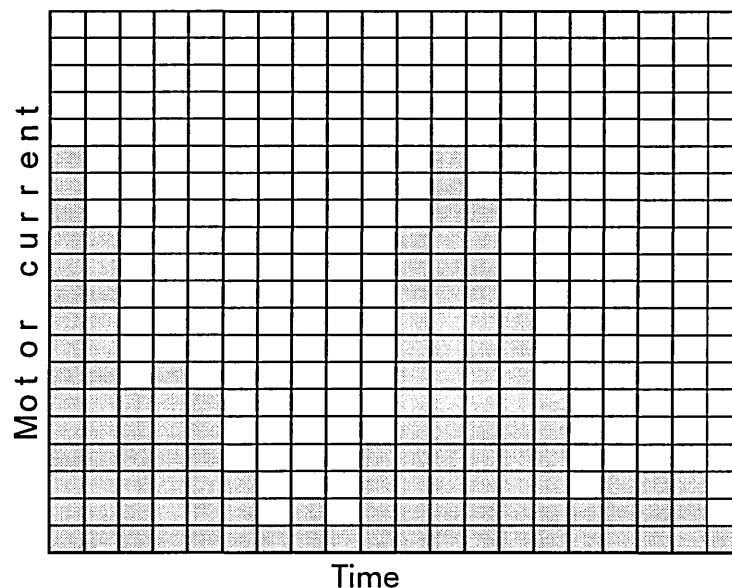
- A running average filter could be applied to one of the sets of data to compensate for any minor offset in the time domain.
- To overcome offset errors, each data value in *setA* could be compared to the corresponding data value in *setB* as well as the two immediately adjacent values in *setB* (3 comparisons in total). The minimum error

value is selected and the process is repeated for each data value in setA.

This has the effect of overcoming natural data offset by  $\pm 1$  sample.

### 6.2.2 Data processing and pattern recognition

A second type of error detection algorithm that was considered relates to pattern recognition, which attempts to define the similarity between two or more sets of data. Pattern recognition problems, particularly relating to character recognition, are currently the focus of extensive neural network research. The potential condition monitoring algorithm considered here is much simpler and involves converting the raw door motor data into a number of discrete blocks (see figure 6c for an example), which can then be compared to a known good pattern for analysis.



*Figure 6c: Example of data discretisation prior to pattern recognition analysis*

Conversion of the data into discrete blocks reduces the resolution of the data in both the time and motor current dimensions, which would help to address the data misalignment problem associated with the simple error detection routine described in section 6.2.1. Once the data has been discretised, it could be analysed by any number of analysis algorithms including neural networks, correlation techniques or by simple comparison on a block by block or column by column basis. The data shown graphically in figure 6c

could be stored numerically in a number of different formats, of which two of many possibilities are:

Binary:	1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,0,0,0,0,0,
(20 bits represent 1	1,1,1,1,1,1,1,1,1,1,1,1,1,0,0,0,0,0,0,0,
column)	1,1,1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,
	(only data for first 3 columns shown)
Integer:	15,12,6,7,6,3,1,2,1,4,12,15,13,9,6,2,3,3,1
(by column)	

The main disadvantage of this approach is that an additional data analysis algorithm is required. The flexibility of the data processing is the main strength of this methodology, but the analysis quality depends upon:

- the number of blocks in the time dimension;
- the number of blocks in the motor current dimension;
- the scaling factor for the motor current data;
- the filters used to further process the raw data (user-definable).

Selection of a suitable data processing algorithm could ensure that the final analysis algorithm is much more reliable and robust.

### 6.3 Neural networks

Neural networks were considered to be a potentially viable method of analysing door motor current characteristics in order to classify door performance and identify incipient faults. For this reason, a study of current neural network technology was undertaken to answer the following questions so that the suitability of neural networks could be assessed<sup>24,25,26</sup>.

- What can neural networks achieve?
- How are neural networks created and how do they function?
- What are the advantages and disadvantages of neural networks?

Neural networks have been extensively researched for a wide range of purposes, including engineering control, condition monitoring<sup>27,28,29,30,31</sup> and railway applications<sup>17,20,32</sup>. Research continues to be undertaken to improve the performance of neural networks so that they can be used in increasingly complex applications. Based upon this review of current neural network research, applications and performance, it was clear that neural networks would not form the basis of a suitable condition monitoring solution for electric train doors. The major argument for this is that neural networks require extensive training before they can reliably identify and classify data. The training process involves presenting a large number of different data to the neural network for a correctly operating door<sup>17</sup>. The procedure must be repeated to train the neural network to recognise each individual fault condition. This training procedure would involve an unacceptable level of data collection from a fleet of trains and would also have to be repeated for every different class of train and, as discussed previously, the current characteristics of faulty doors are probably not known. If this approach were adopted, it would be necessary to collect data from an entire fleet of train doors just to calibrate the condition monitoring tool. A large number of doors would also have to exhibit fault conditions, which is clearly unlikely and impractical.

## 6.4 Fuzzy logic

Fuzzy logic is similar to Boolean logic, except that where Boolean logic only recognises two logic states, true or false, fuzzy logic allows the definition of an infinitely variable logic state<sup>33,34</sup>. Fuzzy logic is powerful because it allows logical expressions to be determined where the relationship between variables is not adequately described using standard Boolean logic. For example, day could be defined using Boolean logic as being *TRUE* between the hours of 6am and 6pm (*FALSE* from 6pm to 6am). However, it is clear that day does not end immediately and exactly at 6pm and so the rules are not ideal. Fuzzy logic allows the definition of a state between 5pm and 7pm where it is neither 100% day or 100% night, but a combination of both (e.g. 45% day and 55% night).

Fuzzy logic can be easily applied to aid in the classification of powered train door performance. A requirement of the condition monitoring system is that each door is immediately identified as either operating correctly or abnormally. To do this, it will be necessary to classify the door operation based upon the results of the analysis algorithm. If the analysis algorithm generates a single parameter representing the door performance based upon the raw data, then fuzzy logic could be applied advantageously. Assuming that the condition monitoring analysis algorithm is able to calculate a percentage error value,  $E_{TOT}$ , which is proportional to the deviation of the motor current from the norm, then a fuzzy membership function can be defined (see figure 6d). This membership function classifies the door performance and assigns a confidence level to that classification.

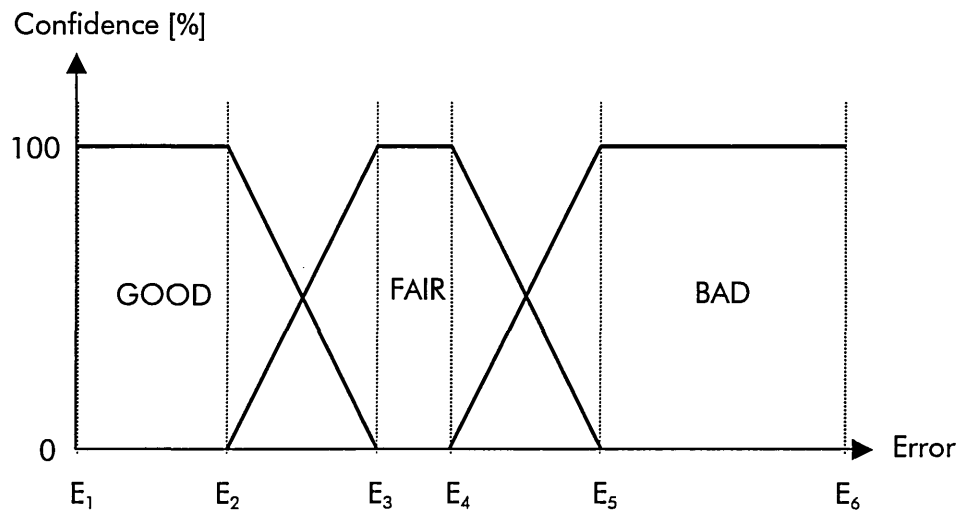


Figure 6d: Generic membership diagram for fuzzy logic door classification

This diagram defines the membership areas and confidence level, of three possible different door performance classifications based upon the value of the single input variable,  $E_{TOT}$ . The corresponding rules are defined in figure 6e. Where the total error for a door analysis lies within the 100% confidence level of a classification band, then the classification will be purely GOOD, FAIR or BAD. However, if the total error lies between  $E_2$  and  $E_3$  for example, then the classification will be both GOOD and FAIR, but the corresponding confidence levels will be proportionally less than 100%, depending on the actual value of  $E_{TOT}$ .

	Classification	$E_{TOT}$	Confidence [%]
1	GOOD	$E_1 < E_{TOT} < E_2$	=100
2	GOOD, FAIR	$E_2 < E_{TOT} < E_3$	<100, >0
3	FAIR	$E_3 < E_{TOT} < E_4$	=100
4	FAIR, BAD	$E_4 < E_{TOT} < E_5$	<100, >0
5	BAD	$E_5 < E_{TOT} < E_6$	=100

Figure 6e: Possible fuzzy logic rules for a condition monitoring classification system

Using fuzzy logic to classify the performance of a train door based upon information derived from the door motor current is a powerful and flexible technique, because it allows logic rules to be defined based on fact, experience and estimation. The fuzzy logic algorithms can be easily reproduced in software code with the variables  $E_1$  to  $E_6$  defined as parameters for flexibility.

## 7. Analysis technique refinement

This chapter of the thesis will detail the final algorithms developed to analyse the performance of electrically powered train doors. Each aspect of the final algorithms will be outlined in order to allow complete understanding of the condition monitoring technique. Chapter 9 of this thesis will address the implementation of these algorithms as embedded software routines forming part of a condition monitoring tool for electric powered train doors.

### 7.1 Normalisation of the door motor data

Normalisation of motor current data in the time domain was quickly identified as a significant step towards the development of a successful data analysis algorithm. Through investigation of raw motor data it was observed that normalisation allows a much simpler direct comparison of motor current characteristics. Although every door on a train should have identical motor current characteristics to other doors on a macroscopic level, on a sample by sample basis each door will exhibit a slightly different response. This will be due to minor differences in the door system (e.g. minor variations in mechanical stiffness, lubrication levels or friction).

Correctly operating doors will also naturally exhibit slight variations in the open and close times, however as shown in section 6.2.1, even small data misalignments could potentially result in large errors when the data is compared on a point by point basis. Normalising the data in the time domain helps to reduce this misalignment resulting in improved performance of the data analysis algorithms. To normalise the data in the time domain, the time index corresponding to each data value is divided by the total motor operating time:

$$t_{i,norm} = \frac{t_i}{t_{total}} \quad (\text{Equation 7.1})$$

In order to maintain full information about the true door performance, it is necessary to record the original total motor operating time before the data was



normalised. This is because the normalisation process can mask incorrect or distorted motor current characteristics in certain situations. Recording the total time of a door to close or open ensures that this information is not lost.

## 7.2 Identification of door motion using the traction interlock

The traction interlock system can be used to identify the direction of door motion so that the correct analysis can be applied to the raw motor data. The traction interlock circuit must be completed before a train can leave a station, which requires all passenger doors on a train to be correctly closed and locked.

When the condition monitoring technique is used to analyse the performance of a door opening cycle, the door must firstly unlock and then open. When the door unlocks, the traction interlock circuit will be broken and de-energised. Conversely, the traction interlock circuit will be completed and energised when the door is closed and locked. Therefore the time,  $T_{INT}$ , at which the traction interlock circuit changes state, as shown by figures 5e and 7a, can be used to identify the direction of door operation:

	$T_{INT}$ (typical) [% of normalised door cycle]	$T_{INT}$ (analysis algorithm) [% of normalised door cycle]
Door opening	0 - 5	< 50
Door closing	75 - 100	> 50

*Figure 7a: Identification of door motion based upon traction interlock signal*

Therefore the condition monitoring technique will identify the door operation as an opening cycle if the traction interlock circuit changes state at a time less than 50 % of the normalised door operation cycle. The algorithm uses a simple technique to identify the operation of the traction interlock circuit. Once the door motor begins operating, triggering the start of data sampling, then each interlock current sample,  $I_i$ , is compared to the previous value,  $I_{i-1}$ :

$$\delta I = |I_i - I_{i-1}| \quad (\text{Equation 7.2})$$

If the value of  $\delta I$  calculated using equation 7.2 is greater than the variable  $\delta I_{MAX}$  (initially set to zero), then the time of interlock operation is defined as time  $T_i$ . This simple comparison is repeated for each sample and, once the sampling is complete, the point of the traction interlock operation will have been identified and recorded. This is based upon the fact that the change in traction interlock current value is greatest when the traction interlock is operated (see figure 5e).

### 7.3 Partitioning of the door motor data into discrete zones

The most important aspect of the data processing concerns the generation of partitions or zones in the normalised motor data. These zones, once identified, will be treated as separate entities by the analysis algorithms and will individually contribute to the final classification of door performance. The normalised data is split into three zones, because this was found to be an optimum balance between insufficient partitioning (1 zone) and excessive partitioning (4+ zones) resulting in inconclusive results or over-complicated algorithms. The three zones are pre-defined within the condition monitoring technique based upon data collected from train doors that are considered to be operating correctly. The zones can be defined in a number of ways:

- Related to physical door movements (i.e. unplugging, sliding, then stopping);
- Related to distinct contrasts in the raw motor data (i.e. high, low current);
- Arbitrary division of the door operating cycle into manageable sections.

	Start index	End index
Zone 1	0	$J_1$
Zone 2	$J_1 + 1$	$J_2$
Zone 3	$J_2 + 1$	99

Figure 7b: Example definition of zone partitions

The normalised door data is represented by 100 integer values and therefore three zones can be defined using two integers,  $J_1$  and  $J_2$ , in the range 0 to 99. It is necessary to define parameters  $X_1$  and  $X_2$  for both the door opening and door

closing cycles, because it is unlikely that the two motor current characteristics will be similar. Figure 7c shows an example of the partitioning of an opening door motor characteristic into three zones.

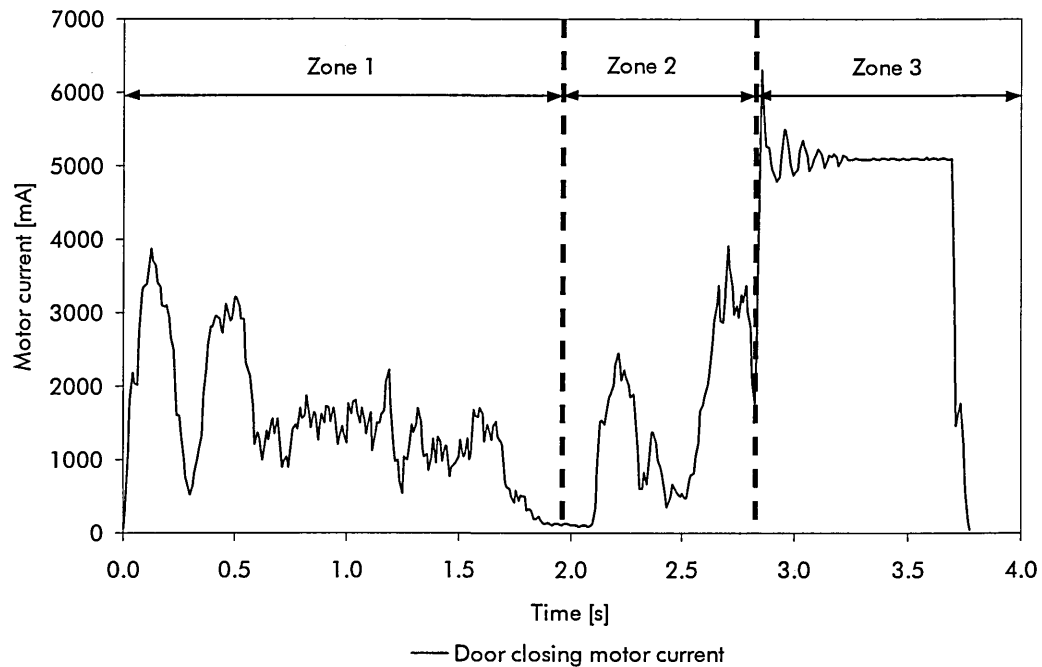


Figure 7c: Partitioning of normalised motor data into zones

## 7.4 Door performance analysis

Once the raw door motor and traction interlock data have been collected, the algorithm must analyse the data so that the performance of the door can be subsequently classified. The analysis algorithm developed for this application is based predominantly on the data relating to the door motor current. Before the data can be analysed it is necessary to know whether the data under investigation relates to an opening or closing door because the motor current characteristic will be different for both cases. The direction of door motion is determined by reviewing the traction interlock data (refer to section 7.2).

The algorithm developed to analyse the performance of electric train doors is based upon the simple error detection methods described in section 6.2. The following steps describe the process of determining the total error for a door motor

characteristic, which forms the basis of the door performance classification. Any constants or parameters must be individually defined for both the opening and closing door cycles.

### 1. Data scaling

The raw motor data are scaled and rounded down to ensure that the data analysis algorithm always analyses values of a known magnitude. This is useful because it means that the magnitude of the calculated error is proportional to the original data.

$$I_{i,scaled} = \text{int}\left(\frac{100 * I_i}{I_{max}}\right) \quad (\text{Equation 7.3})$$

$I_{max}$  is a pre-defined constant defining an estimated nominal maximum current drawn by the motor during the corresponding door motion. For example, if the maximum motor current for a door opening cycle was approximately 5300 mA,  $I_{max}$  could be defined as 5500 mA. Consequently, the magnitude of the scaled data is in the region 0 to 100. Data values can exceed 100 if the maximum motor current exceeds  $I_{max}$ .

### 2. Data comparison

The normalised and scaled data are then compared to pre-defined set of data describing the performance of a correctly operating door. Again two sets of data are required for the analysis, one for door opening and one for door closing. Each set is pre-defined and pre-scaled within the analysis routine and contains 100 data values, which cannot be altered except through re-programming.

To calculate the total error the algorithm compares the normalised and scaled door motor data (array  $I$ ) to the corresponding data that defines the operation of a correct door (array  $X$ ). To account for any misalignment in the data that would cause a large error value to be calculated, as discussed in section 6.2.1, the data are compared using the following equation:

$$E_i = \min \left[ |I_n - X_i| \right]_{n=i-1}^{n=i+1} \quad (\text{Equation 7.4})$$

For each data value in array  $X$  (representing a correct door), three consecutive values in the  $I$  array (door being analysed) are used to calculate an error value,  $E_i$ , which is defined as the minimum absolute error of the three combinations. The algorithm is therefore able to account for the likely misalignment in the data by selecting the lowest error (see figure 7d). This technique is repeated for each of the 100 normalised and scaled data values.

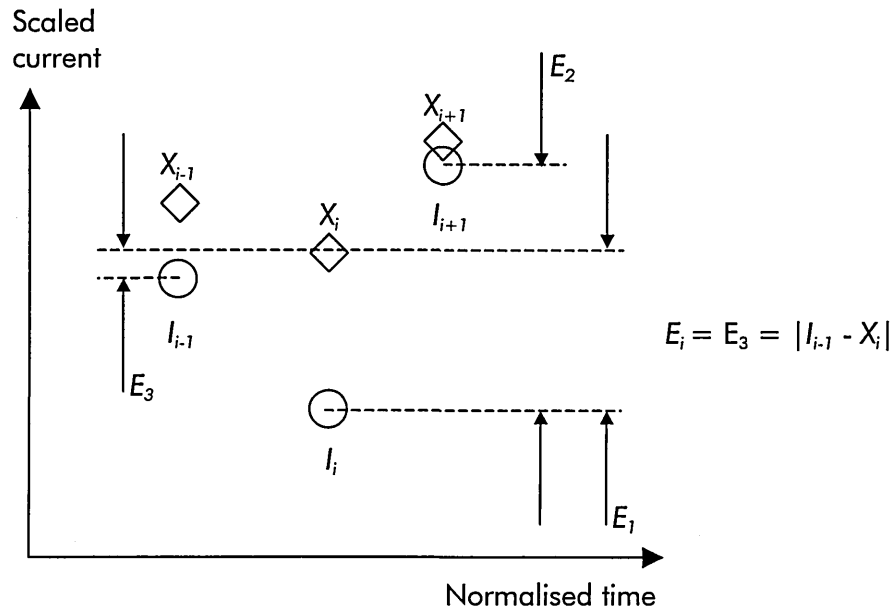


Figure 7d: Diagram showing misalignment-tolerant error algorithm

The three zones of the motor data, which were defined previously in section 7.3, play an important role in the data analysis algorithm. Each data point belongs to one of the three zones and a zone error value is therefore defined,  $E_{Z1}$ ,  $E_{Z2}$  or  $E_{Z3}$ , as the sum of errors in that specific zone:

$$E_{Z1} = \sum_{i=0}^{i=J_1} E_i \quad (\text{Equation 7.5})$$

$$E_{Z2} = \sum_{i=J_1+1}^{i=J_2} E_i \quad (\text{Equation 7.6})$$

$$E_{Z3} = \sum_{i=J_2+1}^{i=99} E_i \quad (\text{Equation 7.7})$$

These three error values are then converted to percentage errors by dividing them by the sum of the data contained within the corresponding zone,  $A_{Z1}$ ,  $A_{Z2}$  or  $A_{Z3}$  (shown in equations 7.8 to 7.10 in summation form):

$$E_{Z1} = \frac{E_{Z1}}{\sum_{i=0}^{i=J_1} I_i} \quad (\text{Equation 7.8})$$

$$E_{Z2} = \frac{E_{Z2}}{\sum_{i=J_1+1}^{i=J_2} I_i} \quad (\text{Equation 7.9})$$

$$E_{Z3} = \frac{E_{Z3}}{\sum_{i=J_2+1}^{i=99} I_i} \quad (\text{Equation 7.10})$$

### 3. Calculation of total error parameter

Once the percentage error values are known for the different zones, it is possible to calculate an overall error,  $E_{TOT}$ :

$$E_{TOT} = \frac{(k_{Z1} E_{Z1} A_{Z1}) + (k_{Z2} E_{Z2} A_{Z2}) + (k_{Z3} E_{Z3} A_{Z3})}{(A_{Z1} + A_{Z2} + A_{Z3})} \quad (\text{Equation 7.11})$$

The zone errors are modified using two factors:

- a 'weighting' factor - the sum of data within the zone ( $A_{Z1}$ ,  $A_{Z2}$  or  $A_{Z3}$ ) taken from array X (the good door data);
- a 'variability' factor in the range 0.0 to 1.0 ( $k_{Z1}$ ,  $k_{Z2}$  or  $k_{Z3}$ ).

The weighting factor ensures that zones, where the current is on average low, will contribute less to the total error than a zone with a higher average current. The variability factor, which is usually set to unity (1.0), allows the analysis algorithm to be robust for cases where the motor current varies substantially during normal operation. For example, if the motor current in zone 3 was known to vary by roughly 20% in normal operation, then this

could result in a large total error. By setting  $k_{z3}$  to 0.75 for example, the contribution of  $E_{z3}$  is reduced, minimising the impact of the motor current variability on the total error value.

## 7.5 Classification of door performance

The performance of each door opening or closing cycle is classified based upon the value of the total error parameter calculated by the performance analysis algorithm (see section 7.4). A simple fuzzy logic algorithm is used to classify the door performance as either 'good', 'fair', 'bad' or a combination (e.g. 'good' to 'fair' or 'fair' to 'bad'). See figures 6c and 6d for further information.

Classification	$E_1$ [%]	$E_2$ [%]	$E_3$ [%]	$E_4$ [%]
GOOD	$-\infty$	0	10	15
FAIR	10	15	20	25
BAD	20	25	100	$+\infty$

Figure 7e: Matrix defining door performance classifications

A matrix must be created to define the relationship between the input parameter and the associated confidence levels. An example matrix is shown in figure 7e, which contains generic values that should be valid for most door systems. Each classification requires four points to fully define the membership function, represented by points  $E_1$ ,  $E_2$ ,  $E_3$ ,  $E_4$  in figure 7f. A confidence level for each of the three door performance classifications can be calculated based upon the total error,  $E_{TOT}$ . There are three possible outcomes:

1.  $E_1 > E_{TOT}$  or  $E_4 < E_{TOT}$   $E_{TOT}$  falls outside the classification limits. The confidence level is set to 0% (not within classification) and the process is repeated for the next classification.
2.  $E_2 \leq E_{TOT} < E_3$   $E_{TOT}$  falls within the maximum confidence level for the classification and the confidence level is set at 95%<sup>6</sup>.

<sup>6</sup> 95% is the maximum confidence level assigned to a classification, because it is not possible to state with 100% certainty that the classification is correct.

3.  $E_1 \leq E_{TOT} < E_2$   $E_{TOT}$  falls within the fuzzy region. The confidence level for the classification must be calculated using the following formulae (confidence is between 0% and 95%).
- $E_3 \leq E_{TOT} < E_4$

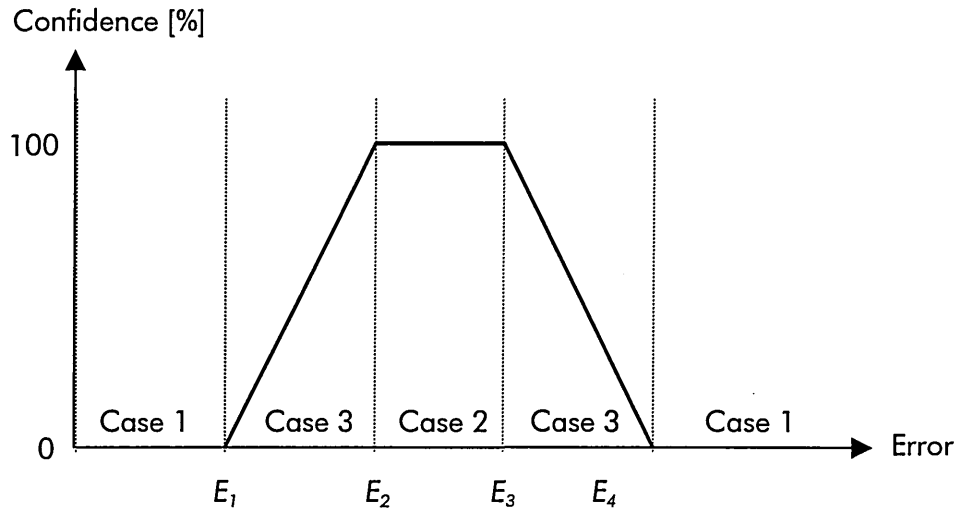


Figure 7f: Example definition of a generic door classification

Formulas 7.12 and 7.13 are used to calculate the confidence level of a classification for Case 3 as defined in figure 7f. Equation 7.12 calculates the interpolation factor, which is then used by Equation 7.13 to derive the confidence level for Case 3.

$$\text{Interpolation factor, } X = \frac{(E_2 - E_{TOT})}{(E_2 - E_1)} \quad (\text{Equation 7.12})$$

Equation 7.12 is slightly different if  $E_3 < E_{TOT} < E_4$ :

$$\text{Interpolation factor, } X = 1 - \frac{(E_4 - E_{TOT})}{(E_4 - E_3)} \quad (\text{Equation 7.12a})$$

$$\text{Case 3 confidence} = 0.95 * \left( \frac{1}{1.0 + e^{\left(10 * \left(X - \frac{1}{2}\right)\right)}} \right) \quad (\text{Equation 7.13})$$

Equation 7.13 limits the maximum confidence to 95% and maps an S-shaped curve to the confidence level transition throughout Case 3, hence creating a



smooth transition between case 1 (0% confidence) and case 2 (95% confidence). Where the total error parameter falls between two classifications (case 3), then the sum of all confidences will equal 95% (e.g. fair 40%, bad 55%). Equation 7.13 was selected after investigating different methods of smoothing this transition using a spreadsheet analysis.

## 7.6 Calculation of descriptive and statistical parameters

The division of the door motor characteristic into three zones allows the effective use of statistical parameters to define door performance. The effectiveness of the parameters to identify faults is partly dependent on the definition of the zones. Descriptive parameters can be divided into two distinct groups, namely those based upon the entire raw data and those from a specific zone.

### 7.6.1 Parameters derived from the entire raw data

The following parameters are derived from the complete set of raw data:

1. Door identification code [-]
2. Date and time of data collection [dd.mm.yy hh:mm]
3. Door action (0 = opening, 1 = closing)
4. Point of interlock operation as a percentage of motor operation [%]
5. Motor operating time [s]
6. Door performance classification - Good door [%]
7. Door performance classification - Fair door [%]
8. Door performance classification - Bad door [%]
9. Total calculated error [%]

These parameters provide important, basic information about the door performance analysis. The data identifies the specific door in question as well as the time and date of the door performance analysis, forming an auditable and traceable record of the results. The direction of door motion (opening or closing cycle) is recorded with the time taken to open and the point at which the interlock was operated. Finally, the results of the analysis

are provided, showing the classification and associated confidence levels as well as the total calculated error. This allows the identification of incorrectly operating doors and could be used as the basis of a high-level door-by-door fleet report. For more detailed information about the potential fault, the parameters derived from the individual zones must be reviewed.

### 7.6.2 Parameters derived from a specific data zone

The following parameters are derived from each raw data zone (i.e. 21 parameters are calculated in total for the 3 zones):

1. Zone error [%]
2. Zone mean error [%]
3. Zone maximum error [%]
4. Zone maximum current [mA]
5. Zone mean current [mA]
6. Zone current variability [mA]
7. Zone sum of current [A]

The first three error parameters are calculated as part of the data analysis algorithm as described in section 7.4. The maximum and mean parameters are useful for identifying changes in the data within a zone. For example, a higher than normal mean current would imply that the door motor is generating more torque throughout the zone. If the maximum current value is substantially higher than normal but the mean current remains roughly normal, this implies that the door mechanism is stiff at a specific point through the operating cycle.

The zone variability parameter is calculated by summing only the motor current data that is greater than the mean current, calculated previously, and then dividing by the number of summed values. This parameter indicates the data spread about the mean and is useful for understanding how well the mean parameter represents the data in that zone. For example, if the mean and variability parameters are similar in magnitude, then the data in that zone is tightly packed about the mean. However, if the variability parameter

is significantly larger than the mean current parameter, then the data varies much more about the mean, as shown in figure 7g.

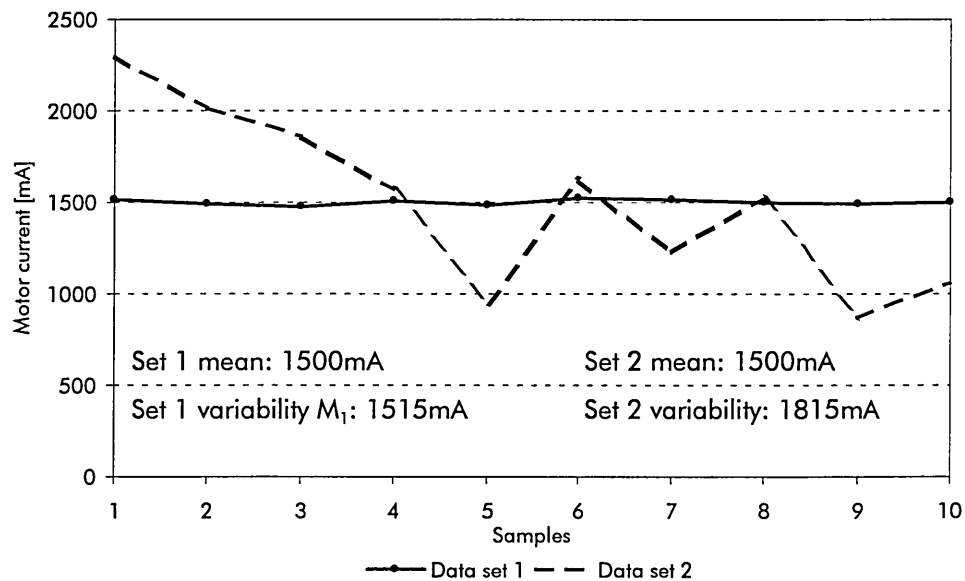


Figure 7g: Graph showing use of mean and variability parameters

The zone sum of current parameter is calculated by summing all of the motor current values in a zone. This parameter provides useful information relating to the area under the current vs. time graph, which is comparable to the power consumed by the motor. The power is actually represented by the integration of motor current squared, however the sum of current parameter is simpler to calculate and provides similar information for a uni-directional current (d.c.). It enables the identification of increased or reduced current consumption in each zone.

The information provided by these two groups of parameters should allow a wide range of different door faults to be identified. Some of the parameters will enable faults to be identified independently, whilst other parameters will highlight faults when reviewed in combination with other parameters. The condition monitoring system end-user will gain knowledge and experience of reviewing and interpreting the descriptive parameters through repeated use of the tool.

## 8. Prototype Door Analysis Tool

This chapter of the thesis will present the design of the prototype Door Analysis Tool (DAT), which represents the major deliverable of the TCS project. The prototype DAT was developed so that Interfleet Technology could evaluate whether the concepts, ideas and solutions developed through the TCS project and presented in this thesis form the basis for a saleable railway condition monitoring product for electric powered train doors. The design of the prototype DAT can be split into two main sections, which will be discussed in more detail:

1. Analogue and digital circuitry;
2. Enclosure incorporating the operator interface components.

The circuitry and essential control software were developed in conjunction with an experienced SHU electronics lecturer, Alan Goude. The TCS project team decided that it would be the most effective use of time and resources to exploit SHU experience to design the electronic aspects of the DAT to a defined specification (appendix B).

### 8.1 Analogue circuit design

The first role of the analogue circuitry is to provide the power supply for the DAT. The specification stated that power should be supplied from a battery to enable the tool to be portable. Standard, rechargeable 9 V PP3 cells were selected due to their small size and their ability to supply the required current at the 5 V required by solid-state electronic components. The supply is regulated by a 5 V regulator (component LM7805, appendix F). The DAT consumes an estimated average current of 60 mA (excluding LCD backlight) and so the operating life from the single PP3 cell is approximately 2 hours<sup>7</sup>. A second 9 V PP3 cell provides power for the LCD backlight, because the current consumption of the backlight is relatively high at approximately 80 mA, and therefore this maximises the life of the DAT main power supply.

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<sup>7</sup> The capacity of the PP3 cell is 120 mAh.

The second role of the analogue circuit is to provide an interface between the input data signals, generated by the two current clamps, and the ADC microchip mounted on the PCB, which converts the analogue input signals into digital signals prior to processing by the microprocessor. This interface is extremely important because it performs a number of functions (refer to appendix C for the analogue amplification circuit schematics):

1. Door motor current signal amplification

The current clamps generate a voltage signal proportional to the sensed current (100 mV/A). During door monitoring and testing at train maintenance depots, the maximum observed motor current was 6.5 Amps. Therefore the maximum input signal was defined as 1000 mV, which is equivalent to 10 A motor current consumption. The input signal range of the ADC is 5 V and full use of the input range ensures maximum accuracy of the signal conversion as stated by the manufacturer. Consequently an amplification factor of 5 was specified for the door motor signal channel (see figure 8a).

2. Traction interlock signal amplification

The signal from the second current clamp, which measures the traction interlock current, also needs to be amplified. The traction interlock signal is small in comparison to the door motor current, being of the order of 25 mA to 50 mA, though smaller or larger signals are possible.

A gain of 23 was selected as the amplification factor for this input channel to use a greater range of the ADC input. A larger gain could have been selected to use the entire 5 V range of the ADC input, however this would have introduced certain disadvantages. With higher amplification factors, circuitry damage could occur if an excessively large signal were applied to the input. A higher amplification factor on the second channel could also interfere with the amplification of the door motor signal.

3. Signal rectification

The signal generated by the current clamps is dependent upon the direction of the sensed current flow. The sense of the output voltage signal would change (i.e. from +0.1 V to -0.1 V) if the direction of current flow through the clamp changes whilst maintaining a consistent current of 1 A.

However the ADC only accepts +ve input signals, which would require the operator to connect the current clamp in the correct orientation prior to analysing door performance. This would make the DAT more difficult to use and less user-friendly. To overcome this problem, both input signals pass through a signal rectification circuit, which maintains the magnitude of the signal but changes the sense so that only positive signals are presented to the ADC (refer to figure 8a).

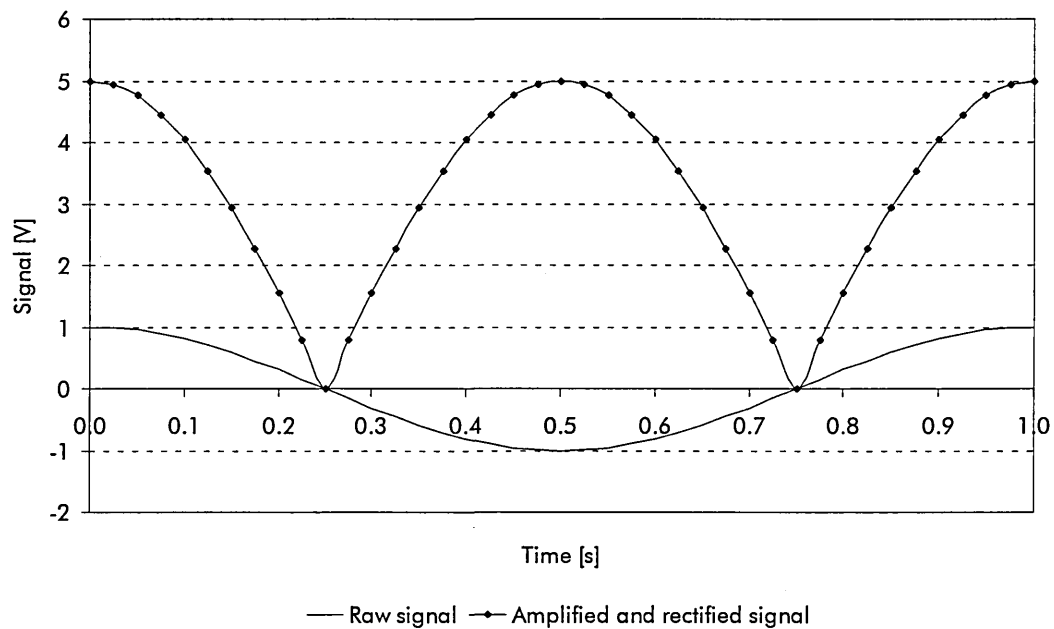


Figure 8a: Data showing door motor signal rectification and amplification process

## 8.2 Digital circuit design

The design of the digital circuit is primarily dictated by the interface requirements of the selected components (refer to appendix D and appendix E for more information about the electronic components). The digital components can be divided into the following main groups:

## 1. Microprocessor

The microprocessor (Philips P89C51RD+) controls all aspects of the DAT and interfaces with all other digital components. The microprocessor requires a simple reset circuit so that in the case of a software fault it is possible to physically re-boot the microprocessor. This circuit comprises a switch (momentary, normally open), a capacitor, a resistor and a diode. Additionally, the microprocessor requires a crystal oscillator (clock) input to use as timing reference. The selected clock for the DAT operates at 12 MHz, but the microprocessor can operate from 0 MHz to 33 MHz<sup>35</sup>.

The P89C51RD+ instructions can be written in the C computer language with a microcontroller-specific compiler. It features on-chip FLASH program memory with In-System Programming (ISP) capability, allowing the software stored within the microcontroller to be re-programmed using only a standard PC in conjunction with an RS232 interface and a free software package. The compiler converts the high-level software code into hexadecimal instructions specific to the microcontroller, which are loaded into the program memory using the ISP software.

## 2. Operator interface components

The keypad (Storm 700 series) is a simple device that is directly connected to the microprocessor via port 1 bits 0 to 7. Only 8 bits are required to detect the operation of the 16 keys, because the keys are inter-connected in a matrix arrangement, as shown by figure 8b. For example, bits 2 and 6 are pulled low if key 11 is pressed, which can be decoded using a simple software routine.

The LCD screen (Powertip 24x2 LCD module) interfaces with the PCB for the power supply and is connected directly to the microprocessor via port 0 bits 0 to 7. Only bits 4 to 7 are used by the microprocessor to send data to the LCD screen and bits 0 to 3 are used for control commands. The LCD unit has a number of in-built functions such as cursor control, display scrolling

and definition of up to 8 custom characters within the LCD Random Access Memory (RAM).

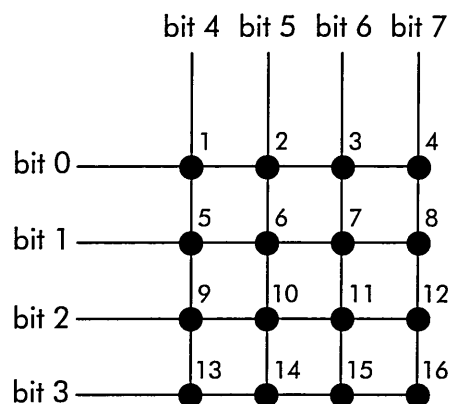


Figure 8b: Keypad matrix connections

The selected LEDs (Dialight 559 series) operate from the PCB 5 V d.c. power supply. One leg of each LED is connected to the microprocessor via port 2 bit 0 (red LED), bit 1 (yellow LED) and bit 2 (green LED). The microprocessor pulls the corresponding bit low to illuminate the LED.

### 3. Other solid-state devices

The 32 Kbyte serial EEPROM (Microchip 24LC256) requires a power supply ( $+V_{CC}$  and  $GND$ ) and communicates with the microprocessor via the *SCL* and *SDA* pins. The EEPROM device address is defined by the pins 1, 2 and 3, which in this case are connected to ground giving a device binary address of 000. It is possible to address up to eight serial EEPROM devices by setting the logic levels on these pins using  $GND$  (0 V) or  $+V_{CC}$  (5 V) (e.g. 001, 010 or 011), allowing the microprocessor to access 256 Kbytes of storage.

The RS232 port device (Maxim RS-232 transceiver) requires a power supply ( $+V_{CC}$  and  $GND$ ) and communicates with the microprocessor via port 3 bits 0 and 1. Capacitors are used as directed by the manufacturer and the device transmits to the physical RS232 port on the DAT casing via three wires. The RS232 device converts the data transmitted by the microprocessor in a standard form that can be interpreted by a standard PC (ASCII format).



The ADC (Linear Technology LTC1288) requires a power supply (+V<sub>CC</sub> and GND) and communicates with the microprocessor via port 3 bits 2, 3, 4 and 5. The inputs to the ADC are the outputs from the analogue signal amplification circuit, which are converted to a digital value in the range 0 to 4095 (equivalent to 0 V to 5 V).

The final device in this category is the real time clock (RTC) (Dallas Semiconductor DS1307) that provides the microprocessor with the date and time using a battery back-up. The device requires a standard power supply in addition to the battery and a 32768 Hz crystal oscillator. It communicates with the microprocessor via the SCL and SDA pins.

### 8.3 Selection of user interface components

This section identifies the components required by the operator to control the DAT. These components are all mounted on the front panel of the enclosure and form the interface between the microprocessor and the operator. The role and reason for the selection of each component will be discussed (see appendix F for further information relating to these components).

#### 1. Display screen

The display screen allows the operator to visually interact with the DAT. The screen displays menus, messages, options and information to the operator enabling them to analyse the performance of electric passenger train doors. The messages displayed on the screen are defined and controlled by the embedded software in the microprocessor. Alphanumeric liquid crystal displays (LCD) were deemed most suitable due to their low power consumption and ease of integration with the microprocessor. A 24x2 LCD (24 characters by 2 rows) (Powertip) was selected as a compromise between display area and physical size. The LCD module features contrast control, a built-in backlight with brightness control and the ability to display a wide range of ASCII characters as well as eight user-definable characters that can be used to generate custom graphics.

## 2. Data entry keypad

The operator uses the data entry keypad to interact with and control the DAT. The minimum functional requirement for the keypad was to the ability to enter numerical values in the range 0 to 9. This is because each rail vehicle in the UK can be identified by a unique five digit code and each door on the vehicle is identified using a one digit code (1 - 4 or A - D). A 16-digit keypad (Storm 700 series) was selected that allows user-definable symbols to be mounted on the face of each key. The keypad also features excellent environmental protection, whilst the six non-numerical keys will allow the operator to perform additional functions such as 'select', 'cancel', 'increment' or 'decrement'.

## 3. Battery holder

The DAT operates from a minimum of one 9 V PP3 cell, but a second cell is required to operate the LCD backlight. The cells could be mounted within the DAT, however it would be inconvenient to dismantle the tool simply to replace a discharged cell. A battery holder (Bulgin) allows the cells to be mounted from the front control panel, allowing easy access to the cells. A battery holder was selected that holds two PP3 cells and allows the cells to be independently changed through the removal of a cartridge. No tools are required to remove a cell from the holder and the cartridge locks securely in place to ensure correct electrical connection.

## 4. Indicators

The purpose of the LEDs is to provide the operator with a visual indication of the door analysis result, where Green = Good, Yellow = Fair and Red = Bad. The LED indicators (Dialight 559 series) were selected for the following reasons:

- Available in red, yellow and green;
- Operate from a 5 V d.c. power supply and feature an internal resistor;
- Snap fit (using retaining flanges), making them easy to assemble.

#### 5. Communication port

The communication port (FCT Electronic) allows the DAT to communicate with a PC. A standard D-type connector was selected to enable RS232 communication via the PC serial port. The port is primarily used to upload data from the DAT to a PC for further interpretation or storage, however it also facilitates microprocessor reprogramming. The connector is sealed using a rear-mounted o-ring and provides excellent environmental protection, which will help to minimise moisture / dirt ingress.

#### 6. Power switches

Two power switches control the power supply to the DAT and the LCD backlight. A switch (Apem) was selected that met both the electrical and the environmental requirements outlined below:

- Two states (on and off);
- The main power switch had to be double pole, but the LCD backlight switch could be single pole. This allows the LCD backlight to be connected such that power can only be supplied to it when the DAT is switched on (refer to appendix C);
- Environmental protection, where possible.

#### 7. Signal input sockets

The selection of the signal input sockets was restricted because they have to interface with the current clamps' connections, which are 'twist and lock' BNC type plugs. A suitable socket was selected that features positive and negative connections, with the negative connector isolated from the connector body. This helps to minimise input signal noise and interference.

### 8.4 Design of casing and front panel layout

The DAT is designed for use in train maintenance depots by engineers or fitters. Therefore the electronic and user-interface components need to be housed within an enclosure to protect them from damage, moisture or dirt. To minimise the prototype construction costs, an off-the-shelf enclosure was identified (refer to

appendix F) featuring a removable, flat aluminium front panel of sufficient surface area to allow the components to be adequately mounted. This minimised the manufacturing costs, because the machining and assembly of the front panel could be undertaken using the SHU workshop facilities. The enclosure does not offer any specific level of environmental protection, however this was considered a minor disadvantage for the prototype design. The enclosure was sufficiently large to allow the circuitry to be mounted inside, whilst being small and light enough to be hand-held. The design layout of the interface components on the front panel was intended to meet a number of criteria:

1. Physically fit with the available area and volume leaving space for the PCB;
2. Simplify and minimise the DAT manufacture and assembly;
3. Be user-friendly, intuitive and aesthetically pleasing.

A photograph of the completed prototype DAT is shown in figure 8c. All of the user interface components are located on the front panel to minimise the required machining and simplify the assembly process.



Figure 8c: Photograph of the prototype Door Analysis Tool

## 9. Door Analysis Tool software routines

This chapter of the thesis will detail the key areas of the data analysis software, briefly explaining how the analysis algorithms translate into software routines. Only a brief explanation of relevant aspects of the source code will be given, however the associated source code is available (see appendix G). The software algorithms discussed in this chapter follow the same order as the algorithms described in chapter 7.

The Philips Semiconductor P89C51RD+<sup>35</sup> microcontroller was selected to control the operation and perform the analysis functions of the prototype DAT (see appendix E for more information). The microcontroller features 64 Kbytes of program memory, which is sufficient to store the prototype code and allow substantial further software development. It also features 1024 bytes of RAM to temporarily store the sampled door motor data prior to data analysis.

### 9.1 Identification of door motor start and end

The DAT must be able to identify the start and end of the door motor data, which is sampled and stored within the *samples* array. Once the start and end array indices are known, then the data analysis routines can be executed. Operation of the door motor is automatically detected by the *collect\_data* function and so the first door motor current data value is always stored in *samples[0]*. Identification of the end of the door motor operation is handled by the *find\_end* function. The steps for identifying the start of motor operation are:

1. A baseline parameter, *tolerance*, is immediately defined by calculating the average of the first 16 samples collected whilst the door motor is not operating. The *tolerance* parameter defines the observed motor current that must be exceeded before the start of door motor operation is identified.
2. Each subsequent door motor sample is compared with the *tolerance* parameter. If the sampled door motor current, *ch0*, exceeds *tolerance*, then the value is stored in *samples[0]*. Each subsequent door motor sample is stored in the *samples* array until all 300 values have been collected, which represent

6 seconds of data at a sampling frequency of 50 Hz. Door operations normally take a maximum of 5 seconds or less.

The same technique is used to identify the end of the motor data after the 300 samples have been stored in the *samples* array. The only difference is that the *tolerance* parameter is defined by the data value stored in *samples[299]* and the *find\_end* function searches backwards through the *samples* array until the new *tolerance* parameter is exceeded.

## 9.2 Identification of interlock operation

The DAT identifies the point of traction interlock operation using the *collect\_data* function by comparing the change in the sampled value of *ch1*. Only the point in time at which the traction interlock is either gained or lost, *relay\_time* is stored. As each sample is taken, the current sample, *ch1*, and the previous sample, *ch1\_previous*, are compared. If the absolute difference between these parameters is greater than *ch1\_max\_diff*, then the *relay\_time* parameter is defined by the current sample, *sample\_count*. Once the sampling is complete, the *relay\_time* parameter will define the time of traction interlock operation.

## 9.3 Door performance analysis

The DAT analyses the sampled door motor data, in *samples*, using the *analyse\_door\_error* function. Before the algorithm can identify the differences between the sampled data and the pre-defined good motor data, in the two-dimensional *good\_data* array, the parameters defining the three zones, *zone1end* and *zone2end*, must be assigned to variables. The parameters that define the importance of the three zones, *imp1*, *imp2* and *imp3* are also assigned.

The good door data is defined within the code by 100 integers. The algorithm must compare each individual good data value, *good\_data[[i]]*, to an equivalent value derived from the *samples* array. However, the *samples* array will normally

contain between 200 to 250 motor data values and so the algorithm must calculate an interpolated value, stored in *av\_data[2]*, to compare with *good\_data[][i]*. In order to counteract the effect of data offset, the algorithm actually calculates three error values using the three values stored in the *av\_data* array, *av\_data[0]*, *av\_data[1]* and *av\_data[2]*. The minimum of the three errors is selected and added to the error sum corresponding to the current data zone, *rec.z1\_err*, *rec.z2\_err* or *rec.z3\_err*. Before the algorithm repeats the procedure for *good\_data[][i+1]*, it must rotate the data in the *av\_data* array, such that *av\_data[2]* can be filled by the next value and the two previous values are stored in *av\_data[0]* and *av\_data[1]*. The *av\_data[0]* value is no longer required.

The algorithm constantly identifies the maximum error, sums the total error and sums the motor current data for each zone. When the 100 data in *good\_data* have been processed, the mean zone error can also be determined. Finally the total error parameter, *rec.total\_error*, can be calculated using the importance factors, the sum of the zone errors and the sum of the zone motor currents. The door performance can now be classified using this error parameter.

## 9.4 Classification of door performance

The classification of the door performance by the DAT is handled by the *calc\_result* routine using the *rec.total\_error* parameter (previously defined in the *analyse\_door\_error* function). The routine loops three times, which calculates the confidence level of the good (*i = 0*), fair (*i = 1*) and bad (*i = 2*) classifications. The *rec.total\_error* parameter can fall in to one of four options for each classification:

1. *Rec.total\_error* falls outside of the classification band and a confidence level of 0 % is assigned to the parameter *rec.result[i]*.
2. *Rec.total\_error* falls within the band of ascending confidence and so the exact confidence level must be calculated using the equations defined in section 7.5. The result is assigned to the parameter *rec.result[i]*.

3. *Rec.total\_error* falls within the band of maximum confidence and a confidence level of *max\_confidence* (= 99 %) is assigned to the parameter *rec.result[i]*. The maximum confidence level is not 100 % because it is unrealistic to state that the classification is correct.
4. *Rec.total\_error* falls within the band of descending confidence and so the exact confidence level must be calculated using the equations defined in section 7.5. The result is assigned to the parameter *rec.result[i]*.

## 9.5 Generation of descriptive / statistical parameters

Two of the parameters, the door identification code and the date and time of the test are defined through user input prior to the collection of data. Other basic parameters such as the motor operating time, the traction interlock time and the door motion are determined in the *find\_end*, *collect\_data* and *door\_action* routines respectively.

The remaining descriptive parameters, detailed in section 7.6, are calculated either during data analysis by the *analyse\_door\_error* function or by the *calc\_parameters* function. The 9 zonal error parameters (e.g. *rec.z1\_err*, *rec.z1max\_err* and *rec.z1av\_err*) form part of the main analysis routine and must be calculated to derive the overall error parameter *rec.total\_error*. The other 12 zone descriptive parameters (e.g. *rec.z1\_imax*, *rec.z1\_imean*, *rec.z1\_imod\_mean* and *rec.z1\_isum*) do not form part of the analysis, but are calculated so that subsequent trend analysis can be undertaken by the operator of the DAT.



## 10. Practical testing of the Door Analysis Tool

This chapter of the thesis will briefly address the practical testing that was carried out with the prototype DAT. The objectives of the practical tests were to ensure that the DAT:

- Functions correctly in a train depot environment;
- Allows the collection of raw data to aid the generation of good door characteristics;
- Correctly identifies and interprets the traction interlock signal;
- Correctly classifies normal doors as GOOD and abnormal door operation as FAIR or BAD depending on the observed deviation from the pre-defined characteristic;
- Facilitates the investigation of door faults.

The practical testing was undertaken at a train maintenance depot in Leeds in conjunction with a new-build EMU fleet with the support of the fleet commissioning team, which allowed the performance of the prototype DAT to be proven. The prototype DAT was successfully programmed based upon the door motor characteristic of the fleet. Doors exhibiting the defined correct characteristic were accurately classified as good, whilst doors whose performance was artificially impaired (by attempting to stop the doors closing) were correctly classified as fair or bad, depending upon the level of interference. During testing, a couple of passenger doors were identified that were incorrectly set-up. One of the faults concerned the incorrect setting of a microswitch, resulting in the continuous operation of the motor even once the door was closed. This would have caused the motor to burn out and fail prematurely.

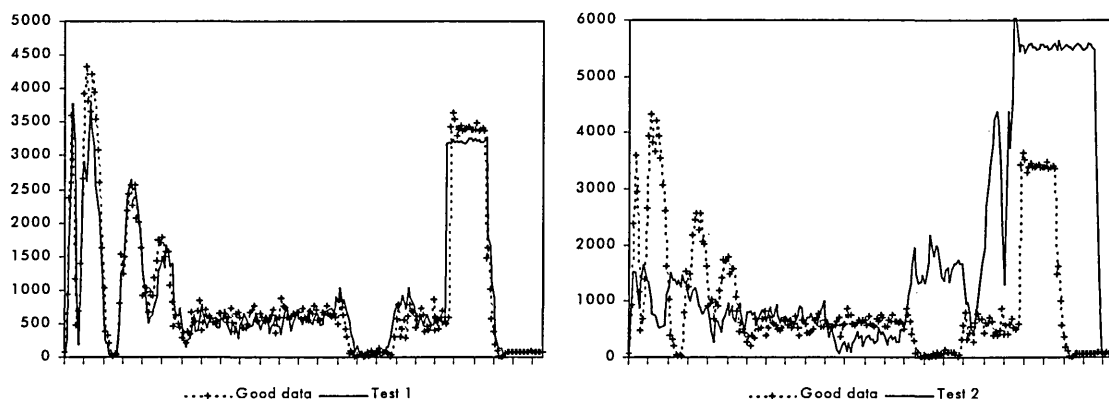
The practical testing of the prototype DAT was extremely valuable, because it proved that it could achieve the objectives outlined above and that the tool was suitable for use in a depot environment. Further use of the DAT by the fleet maintenance team should enable them to identify faulty train doors. It is also likely that further use of the tool will help to identify further areas of product improvement or refinement.

## 11. Theoretical testing of the Door Analysis Tool

This chapter of the thesis aims to show that the DAT is able to identify faulty electric powered train doors by analysing the door motor current characteristic. A special software function was developed to enable the DAT to undertake this theoretical testing, allowing the DAT to analyse and classify pre-defined door motor data stored within the program memory of the microcontroller. To change or re-define the door motor data held in the program memory, the source code must be modified, re-compiled and the microcontroller re-programmed.

The theoretical testing comprises nine specific sets of artificially generated door motor data, where each test represents a potential mode of door failure. The testing focuses on the opening cycle of a sliding plug type door and the good door definition is based upon data collected from a new EMU fleet. These tests do not simulate the traction interlock signal and so the operator must indicate that each test represents an opening door. The test data are defined by figure 11a and represent:

1. A correctly functioning opening door;
2. A correctly functioning closing door;
3. An opening door with no damping function when fully open;
4. An opening door with slight stiffness during unplugging motion;
5. An opening door with increased stiffness during unplugging motion;
6. An opening door with increased stiffness during sliding motion;
7. An opening door that is slow to open;
8. An opening door that is quick to open;
9. An opening door with a faulty locking mechanism (stiff or damaged)



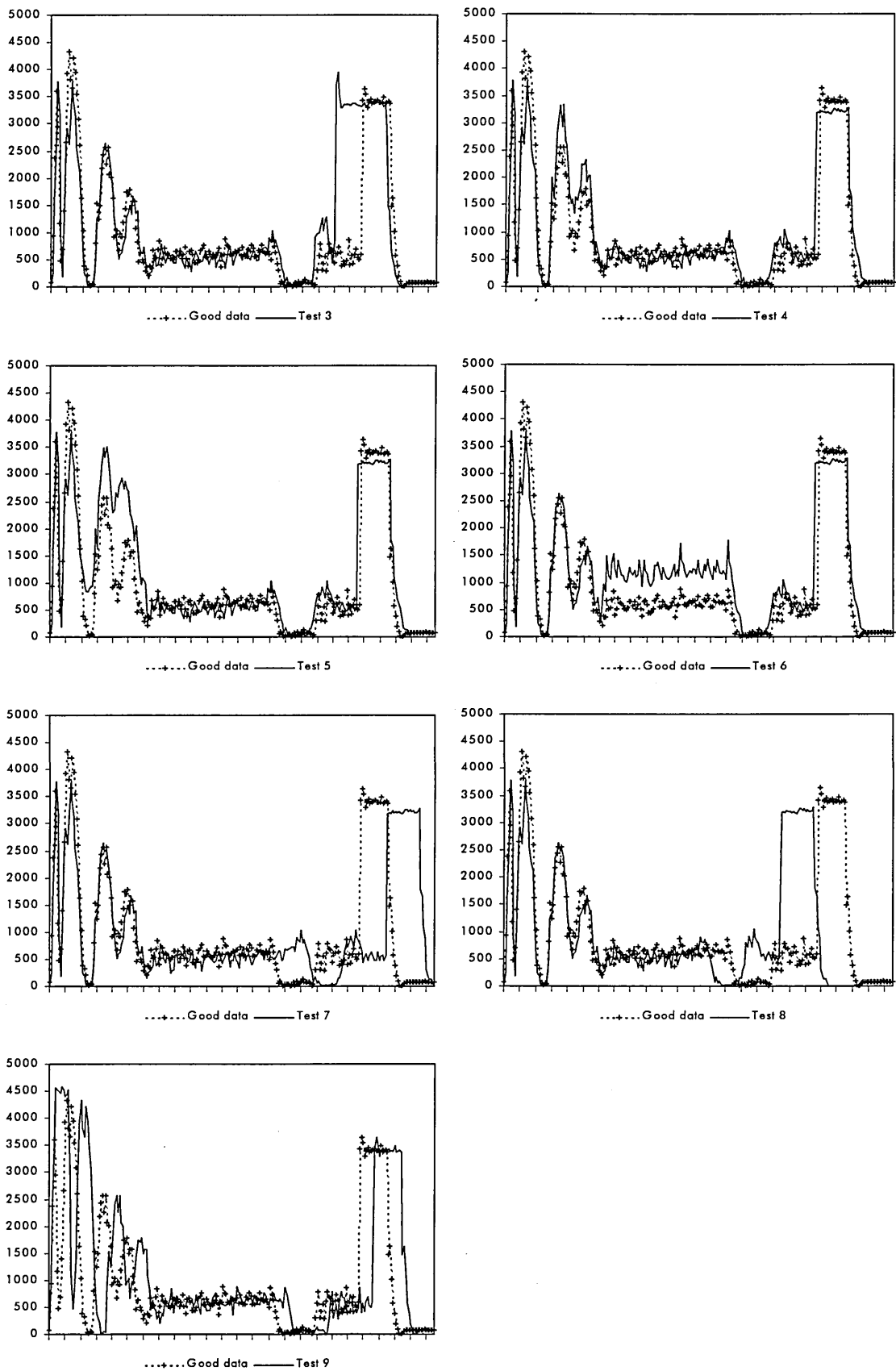


Figure 11a: Graphs showing the raw data for the nine theoretical tests

### 11.1 Results of the theoretical testing

The results of the nine theoretical tests are provided in tabular format in appendix H. The shaded cells highlight the parameters that identify the particular failure mode represented by the test. The test results were transferred from the non-volatile memory of the DAT and copied directly into the table. For all of the tests, the variability factors were defined as  $k_{z1}=1.0$ ,  $k_{z2}=1.0$  and  $k_{z3}=0.5$ . Factor  $k_{z3}$  was defined as 0.5 because zone 3 contains a significant block of data (that is largely unimportant), which could cause spurious error warnings to be generated. Reducing the factor to 0.5 reduces the impact of the zone 3 error on the total error calculation. A short review of the test results will be undertaken for each of the nine tests.

- Test 1 The data represents a correctly operating opening door, which is confirmed by the 'good' classification and the low zone error values (see appendix H. Error values will never be zero because the door motor data is unlikely to exactly match the definition of a 'good door'.
- Test 2 This test involved motor data for a closing door being incorrectly analysed as an opening door. The door classification is correct because the data does not correspond to an opening door. The operator could identify the mistake by reviewing the raw motor data graphically on the LCD. Alternatively, almost all of the parameters confirm that there is no correlation between the test data and a 'good door'.
- Test 3 Door motion is not damped as it approaches the end stops, causing it to slam open. This is indicated by the abnormally large current consumption at the end of the opening cycle. The door is however still classified as 'good', which is due to the  $k_{z3}$  factor minimising the impact of the error. The fault can be clearly identified by the change in a number of parameters. Modification of factor  $k_{z3}$  would cause the DAT to classify this type of fault as 'fair'. A door with this characteristic would appear to operate correctly, however it could lead to premature wear or damage, if not rectified.

- Test 4 The door in this test suffers from slight abnormal stiffness during unplugging, however the DAT still classifies the door as 'good'. The total error is on the limit of the 'good door' classification boundary (10%) and the parameters do identify this specific fault ( $Z_1$  error and  $Z_1$  I mean). A door with this characteristic could continue to be monitored to ensure that the fault does not become more severe and repaired when next convenient.
- Test 5 This test represents a door with a significant level of abnormal stiffness during unplugging, which causes the DAT to classify it as 'fair'. The nature of the fault is clearly identifiable through the parameters. A door with this characteristic should be repaired as soon as practicable.
- Test 6 The door featured in this test has significant mechanical sliding stiffness. The DAT correctly classifies the condition of this door as 'fair' and the nature of the fault can be clearly identified by reviewing the parameters ( $Z_2$  I mean or  $Z_2$  I sum). A door with this characteristic should be repaired as soon as practicable to ensure that it does not cause an in-service failure.
- Test 7 The door simulated in test 7 takes approximately 0.5 seconds longer to complete the sliding motion, which is identifiable by the *motor time* parameter. The overall error is low, corresponding to a 'good' door, because the normalisation process partly counteracts the extra time. This reduces the data misalignment, but  $Z_2$  error can be seen to be much higher than normal (13%). Door manufacturer specifications often quote opening and closing times as  $\pm 1$  second and so this door would be within tolerance. If the door were to open still slower the DAT should identify greater error, especially since the reduction in door speed should be associated with increased motor current.
- Test 8 The door in this test is roughly 0.5 seconds quicker than normal, which is shown by the *motor time* parameter. This door is classified by the DAT as borderline 'good / fair' and the errors are noticeably higher than normal.

This door is operating within specified parameters, however the DAT does highlight that there may be a fault with the door warranting further investigation when practicable.

Test 9 The door lock fault simulated by this test results in a 'bad' classification by the DAT, which is totally correct. The fault can be quickly confirmed to be in zone 1 by inspecting the  $Z_1$  error parameter. The error is high because of the comparatively small amount of motor data located within zone 1, which could be considered to be misleading. A number of the parameters allow the specific nature of this fault to be readily identified.

## 11.2 Conclusions from the theoretical testing

The results of the theoretical tests showed that the DAT could successfully identify and correctly classify different types of door faults. The results can be summarised as follows:

N° of correct classifications:	6	(tests 1, 2, 5, 6, 8, 9)
N° of incorrect classifications:	0	
N° of inconclusive classifications:	3	(tests 3, 4, 7)
	Total	<u>9</u>
N° of faults identifiable by parameter review:	9	
N° of faults not identifiable by parameter review:	0	

The most difficult tests for the DAT to resolve were test 3 (no damping), test 4 (minor stiffness) and test 7 (door slow to open), because the deviation of the test data from the pre-defined 'good' data was not particularly significant. The analysis algorithm is capable of detecting minor errors in the respective zones, however the impact of small errors can be overwhelmed by the weighting factor of the other data. This is also an advantage, because it allows the doors to exhibit a certain amount of natural variability without flagging fault conditions, which could reduce operator confidence in the tool. In reality, it is also not sensible to identify every minor change in door performance given the large numbers of doors in a fleet. It

is much more important to be able to identify clear door faults before they lead to in-service door failures.

The other tests were all correctly classified in meaningful ways proportionate to the deviation of the door motor characteristic from the 'good' definition. The parameters allow an operator to identify the nature of each fault. This can also be achieved by storing and reviewing the raw motor data, though only 10 complete sets of data can be stored in the prototype DAT due to the size of the raw data (612 bytes), compared to 200+ sets of parameters.

The results of the door tests are highly dependent upon the zone definitions, the 'good' door motor characteristic and the variability parameters. The variability parameter  $k_{z3}$  could have been set at 1.0 rather than at 0.5 in the tests. This change would probably cause test 3 (no damping) to be classified as 'fair', however it would have also increased the impact of inconsequential data mismatch in zone 3 for other tests. This could result in faults being incorrectly predicted, which is potentially a worse situation.

It is a straightforward procedure to define a new set of analysis parameters in order to use the DAT with a fleet of electric train doors. It is also simple to modify existing analysis parameters to tailor the DAT analysis to any type of electric train door. The successful definition and adjustment of parameters will be refined by Interfleet Technology through increased experience of setting up and using the DAT on a variety of different train door systems.

## 12. Future work

The TCS project was successfully completed and resulted in the development of the prototype DAT, a condition monitoring tool for electric powered train doors. This thesis documents the development of the DAT along with theoretical testing highlighting the suitability of the DAT as a condition monitoring tool for the railway industry. However the DAT could benefit from further work, as identified below.

1. Re-development of the DAT

For the DAT to be extended to a production version, the entire design and selection of components and materials should be reviewed in order to improve the environmental protection, ruggedness and overall aesthetics of the final product. The re-development should also take into account relevant legislation applicable to commercial products in the UK or the railway industry.

2. Pneumatic powered train doors

A large number of powered train doors in the UK are powered by compressed air. Further research should be conducted to determine whether a commercially feasible off-line / on-line condition monitoring system can be developed for pneumatic train doors.

3. Integration of the DAT into new-build door systems

The DAT is an off-line system, however the data collection and analysis algorithms could be integrated into new train door systems, as supplied by an original equipment manufacturer (OEM) with minimal re-development work.

4. Identification of other condition monitoring applications

The analysis algorithms developed for the DAT could be adapted for use in a range of similar condition monitoring applications, such as other single-throw systems (e.g. point motors). The algorithms could also be adapted to encompass other wider aspects of railway condition monitoring applications.



### 13. Conclusions

Powered passenger train doors are fitted to a high proportion of passenger rolling stock in the United Kingdom. Powered passenger train doors utilise pneumatic actuators or electric motors to open and close and there is a wide range of designs and operating mechanisms available. They are often one of the most unreliable train sub-systems, a problem compounded by their interaction with the train traction interlock system due to the safety-critical nature of the external doors. This thesis provides detailed information about powered passenger train doors and condition monitoring applications in the railway industry, identifying why a condition monitoring system for powered train doors is needed. This thesis subsequently presents the development of a prototype condition monitoring tool, the Door Analysis Tool, for electrically powered passenger train doors, which was developed by the author through a TCS collaborative project between Interfleet Technology and SHU.

The DAT is designed to be portable, rugged and easy to use so that it can be used in train maintenance depot environments. It is able to analyse the performance of an electric train door by monitoring the door motor current and traction interlock current as it opens and closes. Data collection is non-invasive and safe, therefore requiring no train modification or retro-fitting of components. The DAT is able to immediately classify door performance as 'good', 'fair' or 'bad', and allows the operator to store detailed information for further investigation.

The DAT was tested practically in collaboration with a new-fleet commissioning team, which identified that it was able to operate in a train depot environment and successfully identify correct and faulty door operation.

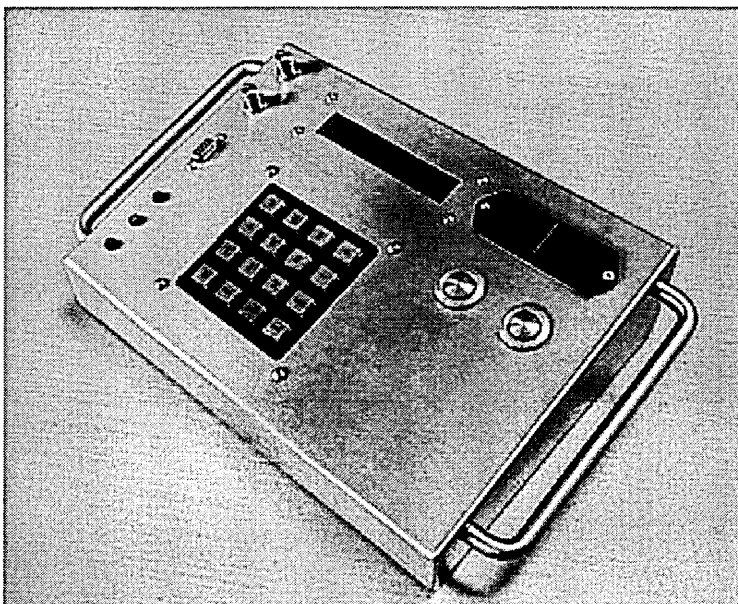
The DAT was also tested theoretically using nine pre-defined, simulated door fault conditions and it correctly classified six of the nine tests. The remaining three simulated door faults were incorrectly classified as 'good'. However, in each case the deviation of the test data from the pre-defined 'good' data was not particularly significant and the stored parameters allowed the incipient fault to be successfully identified. Based upon these tests, it can be concluded that the Door Analysis Tool is a viable condition monitoring tool for electric train doors.

## 14. Author's note

Following the development, manufacture and testing of the prototype Door Analysis Tool as described by this thesis, Interfleet Technology decided that it was a viable commercial product. The future work option 1, outlined in chapter 12 was implemented and an initial batch of ten production versions of the DAT were manufactured. As a result of this review a number of significant improvements were made to the design including:

1. Design and manufacture of a brushed stainless steel casing;
2. Design and manufacture of an integrated PCB (analogue and digital circuits);
3. Re-selection of user interface components to improve environmental protection, durability and suitability for depot environments. Improved component layout;
4. Expansion of on-board memory from 32 Kbytes to 96 Kbytes to improve data storage capabilities. Further software development to improve functionality;
5. Microprocessor upgrade to P89C51RD2 allowing In-System Programming using a 5 V d.c. power supply (i.e. internal power supply), making the DAT truly re-programmable at any external site using only a laptop PC.

The DAT is currently being marketed by Interfleet Technology as a condition monitoring tool for the railway industry. A photograph of the production version of the DAT is shown below in figure 14a for completeness.



*Figure 14a: Door Analysis Tool (production version)*

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## 17. Appendices

### 17.1 Appendix A: Monitoring equipment specifications

This appendix provides an overview specification for key transducers or equipment used whilst developing the prototype DAT.

#### Commerical datalogger (used initially)

Manufacturer	Pico Technology
Product	ADC-11 + screw terminal block
Input channels	11
Input range	0 V d.c. to 2.5 V d.c.
ADC resolution	10 bit
Accuracy	1%
Max. sampling rate	15 kHz
Features	Parallel port connectivity to a standard PC. Complete with logging and display software. Screw terminals for easy transducer connection.
Dimensions: L x W x D	110 mm x 54 mm x 16 mm
Cost	£120.00 + VAT

#### Draw-wire transducer

Manufacturer	RDP Electronics
Product	DWT-10-20-C-1
Weight	1.1 kg
Dimensions: L x W x D	176 mm x 137 mm x 72 mm
Maximum extension	2000 mm
Resolution	0.1% typical
Accuracy	0.2% full-scale maximum
Output signal	0 V d.c. to 10 V d.c. proportional to wire extension
Cost	Unknown - SHU equipment loan

#### Pressure transducer

Manufacturer	Druck Ltd
Product	PMP1400
Maximum pressure	6 bar gauge
Accuracy	±0.15% typical
Output signal	0 V d.c. to 5 V d.c. proportional to pressure
Cost	£148.00 +VAT
Comments	IP65 rated, requires power supply (9 V d.c. to 30 V d.c.)

#### Current clamp

Manufacturer	LEM-HEME
Product	PR30
Maximum current	30 A
Resolution	±1 mA
Accuracy	±1% of reading
Output signal	100 mV/A
Cost	£210.00 + VAT
Comments	Requires internal 9 V PP3 cell.

## 17.2 Appendix B: Specification for the prototype Door Analysis Tool

### Door Analysis Tool performance specification (created December 2000)

This document forms the performance specification for the Door Analysis Tool that is being developed by Alan Goude (Sheffield Hallam University) and Simon Perkin (Interfleet Technology). This performance specification has been developed through detailed discussions and specifies the operating and performance requirements of the door analysis device. The project deliverables are also specified.

#### Inputs

The Door Analysis Tool must:

- Accept voltage inputs from 2 current clamps in the range 0 to 1 Volt (equivalent to 0 to 10 Amps). One channel will record a door motor current and the other channel will record the traction interlock status. Both inputs will be terminated using standard "BNC type" twist and lock connectors.
- Sample both of the input channels at 50 Hz.
- Feature an Analogue to Digital converter with a 10 bit minimum resolution.
- Accept either +ve or -ve voltages from the current clamps and interpret them as +ve data. This will allow the current clamps to be connected in either orientation and will simplify the monitoring process.
- Store the motor current data temporarily in a defined block of memory for subsequent analysis, after which it can be discarded.
- Operate from an internal power supply, probably utilising a standard replaceable/rechargeable battery.
- Allow operator interaction with the door analysis device, probably via a 9 or 16 digit keypad.

#### Outputs

The Door Analysis Tool must feature:

- A LCD (24 characters x 2 rows) with backlighting to enable messages to be displayed for the human operator. The backlight should be switch operated from a separate power supply to maximise the operating life of the device.
- A method to allow stored records to be transferred to a PC, probably via a standard serial-type connection. The records should be transferred as ASCII characters in a specific format (to be defined). The operator will instigate the transfer of the records. The door analysis device will not check for communication errors during the data transfer process.
- A method to allow the door motor current data (last set stored in memory) to be transferred to a PC, probably via a standard serial-type connection. The records should be transferred as ASCII characters in a specific format (to be defined). The operator will instigate the transfer of the records. The door analysis device will not check for communication errors during the data transfer process.

#### Analysis

The Door Analysis Tool must:



- Allow the human operator to identify the door being analysed. The 6-digit code will comprise the unique 5-digit vehicle number and a door identification number. The human operator will enter the 6-digit identification code before analysis begins.
- Identify the point at which traction interlock status changes (code supplied by S. Perkin). If no point is detected, then an error should be generated.
- Generate up to 30 parameters using software (supplied by S. Perkin) based upon the collected door motor data.
- Interpret the generated parameters to enable the operating status of the door under analysis can be determined (code supplied by S. Perkin).
- Allow the parameters to be stored as a complete record in non-volatile memory. The records will be of fixed size and format (to be defined). The record will include the door identification code, the date and time of the analysis, the parameters and the analysis evaluation.
- Present the outcome of the analysis and interpretation to the human operator via the LCD as well as using 3 LED's (green = good, yellow = okay, red = bad).

#### Other

The Door Analysis Tool must:

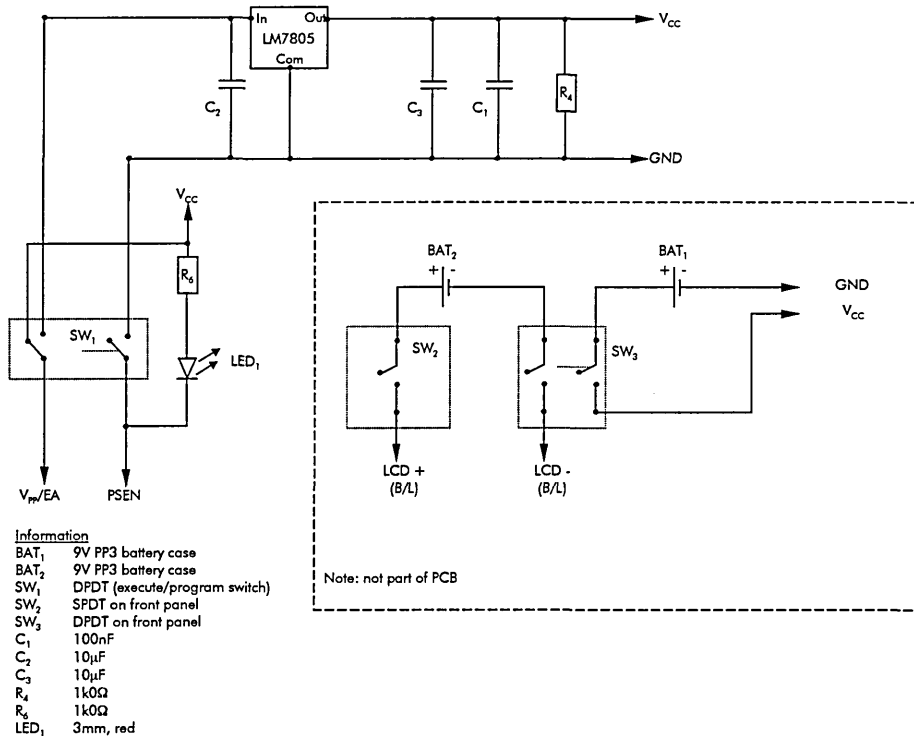
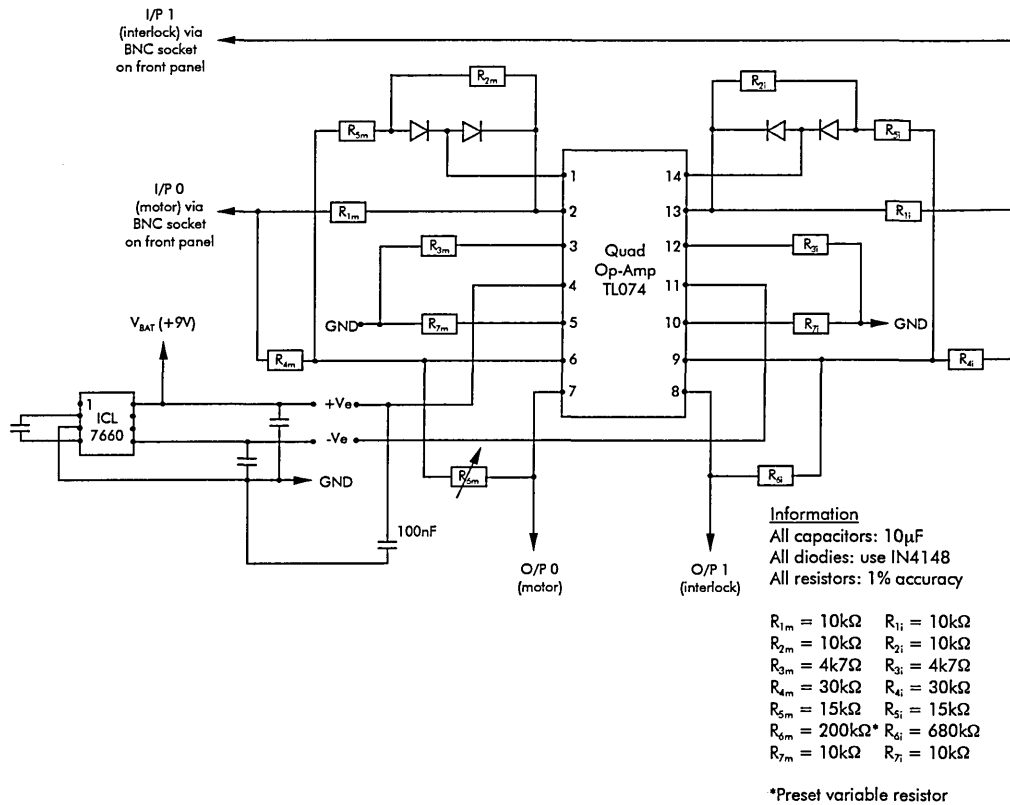
- Have sufficient non-volatile memory to store at least 200 individual records, each containing up to 30 parameters for a duration of at least 6 months.
- Feature a "calibrate" function for the current clamps. This function will continuously display the output from the current clamps allowing them to be correctly zeroed before operation.
- Feature memory management functions. These functions must allow all of the records to be deleted from the non-volatile memory, restore previously deleted records (not on an individual basis) and transfer all records to a PC.
- Allow the human operator to correctly set the date and time.
- Be of suitable dimensions and weight to allow it to be comfortably operated as a hand-held device.
- Feature a power switch allowing the user to turn it on or off.
- Feature components that are suitable for use in a dirty train depot environment and be robust.

#### Project deliverables

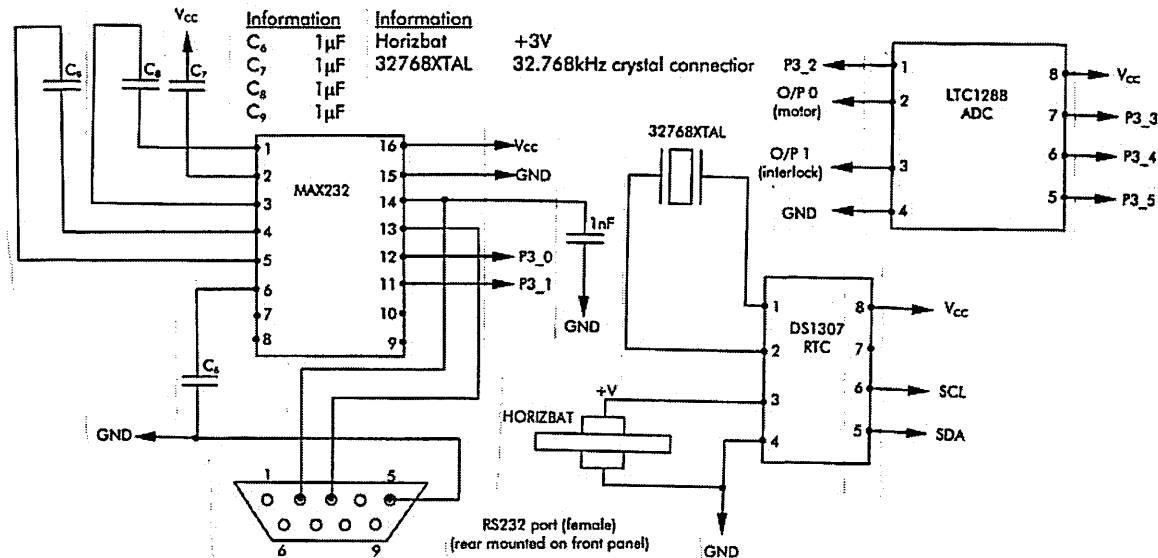
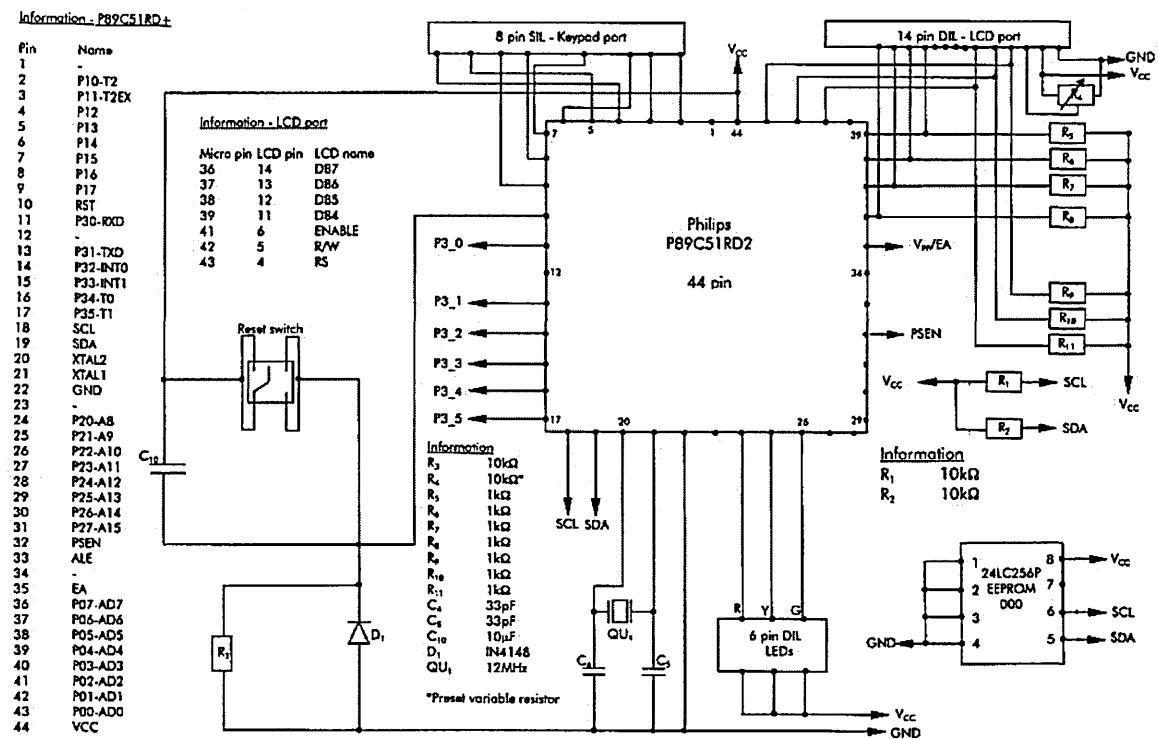
- 1x door analysis device (conforming to the above performance specification).
- All documentation supporting the development, design, procurement, assembly and operation of door analysis device (including source code for the microprocessor in electronic ASCII format).
- Cost breakdown (time and component costs).

Simon Perkin 19.12.2000

## 17.3 Appendix C: Prototype Door Analysis Tool analogue circuits



## 17.4 Appendix D: Prototype Door Analysis Tool digital circuits



## 17.5 Appendix E: Overview of selected electronic components

This appendix provides an overview specification for a number of key electronic components used within the prototype Door Analysis Tool.

Component:            Philips P89C51RD+ 80C51 8 bit FLASH microcontroller

Processor, power supply	80C51 (8 bit), +5 V d.c.
RAM, FLASH program memory	1024 bytes, 64 Kbytes
External addressable RAM	64 Kbytes
Clock frequency	Up to 33 MHz
I/O ports, Timers/counters, Interrupts	4 (8 bit), 3 (16 bit), 7 (4 levels)
Communication	Automatic Address Recognition (UART), I <sup>2</sup> C

Component:            Powertip 24x2 LCD module

Power supply	+5 V d.c. $\pm$ 10%
Interfaces	4-bit or 8-bit data bus
Characters and symbols	192 standard + 8 user-definable characters

Component:            Microchip 24LC256 serial EEPROM

Memory, Cascade	32 Kbytes serial EEPROM, up to 8 devices
Operating voltage	+1.8 V to +5.5 V
Communication	2-wire serial interface bus, I <sup>2</sup> C compatible
Power consumption	3 mA write, 400 $\mu$ A read, 100 nA standby
Write/erase cycles, Data retention	100,000 guaranteed, >200 years
Electrostatic discharge protection	>4000 V

Component:            Maxim MAX232E RS-232 transceiver

Operating voltage	+5 V
Data transfer rate	Up to 120 Kbits per second
Electrostatic discharge protection	$\pm$ 15 kV

Component:            Linear Technology LTC1288 Analogue to Digital Converter

Power supply	+3 V d.c. to +6 V d.c., 160 $\mu$ A typical
Resolution	12-bit
Input	Software selectable 2-channel MUX

Component:            Dallas DS1307 Real Time Clock

Power supply	+5 V d.c., 500 nA in battery back-up mode
Interface	2 wire serial interface
Memory	56 byte non-volatile RAM for data storage

## 17.6 Appendix F: Prototype Door Analysis Tool component inventory

This appendix identifies all of the components required to construct the prototype DAT, including the cost and source of each item.

Item	Component description	Quantity	Supplier	Order code	1-off cost [£]
1	Sloped panel ABS case	1	RS	207-1537	17.48
2	BNC isolated bulkhead socket	2	RS	193-8344	2.64
3	LED (red)	1	RS	311-6748	0.85
4	LED (yellow)	1	RS	311-6776	0.85
5	LED (green)	1	RS	311-6760	0.85
6	SPDT switch	1	RS	219-3700	3.12
7	DPDT switch	1	RS	219-3716	3.74
8	Switch waterproof cover	2	RS	321-228	1.34
9	2x PP3 battery holder	1	RS	501-244	3.49
10	16-way keypad, IP67 sealed	1	RS	198-286	22.21
11	Keypad legend tiles, set A	1	RS	198-084	3.00
12	Waterproof 9-way D-socket	1	RS	195-7395	8.98
13	Alphanumeric LCD (24x2)	1	RS	214-3569	20.95
14	Philips P89C51RD+ microcontroller	1	RS	355-7717	15.27
15	LTC1288 ADC	1	RS	197-1795	9.20
16	ICL7660 voltage generator	1	RS	427-304	1.80
17	MAX232 RS232 level generator	1	RS	225-8510	1.45
18	DS1307 real time clock	1	RS	218-3501	2.22
19	LM317T voltage regulator	1	RS	370-5310	0.24
20	24LC256 serial EEPROM	1	FAR	3001696	3.49
21	12MHz crystal oscillator	1	RS	?	~1.00
22	LM7805 voltage regulator	1	RS	648-488	0.20
23	TL074 quad op-amp	1	RS	182-2441	0.88
24	Power socket	1	RS	486-662	0.39
25	Power connector jack	1	RS	294-7052	2.01
26	Switch (ON-ON)	1	RS	320-938	2.37
27	Lithium coin cell	1	RS	407-977	3.65
28	Misc. resistors and capacitors	-	RS	-	~5.00
29	PCB adhesive guide strips	3	RS	543-973	2.63
30	Misc. wires and cables	-	RS	-	~10.00
Total [£]					150.28

RS = Radio Spares ([www.rswwww.com](http://www.rswwww.com))

FAR = Farnell ([www.farnell.com/uk](http://www.farnell.com/uk))

## 17.7 Appendix G: Prototype Door Analysis Tool source code (partial)

This appendix contains part of the source code from the prototype DAT relating to aspects of the analysis algorithms described in this thesis. The source code is provided to show the implementation of the algorithms within the constraints of an 8-bit microcontroller. The code is presented here with minor formatting changes to improve readability, but is otherwise unchanged.

```

/*****
collect_data

Samples and stores ch0 (motor current) and chl (traction interlock) data for a period of 6
seconds at a frequency of 50Hz (300 samples).

Calculate a motor_current tolerance and sampling begins when motor current exceeds tolerance.
Each sample of traction interlock current is analysed for a maximum change and this time
index is stored and returned as an integer.

Author: Simon Perkin, November 2000
*****/
int collect_data(void)
{
    bit collecting_data = 0;
    int sample_count = 0;
    int ch0_previous = 0;
    int chl_previous = 0;
    int chl_max_diff = INTERLOCK_TOLERANCE;
    int relay_time = 0;
    int tolerance;

    lcd_clear();
    lcd_puts(" Activate door to start");

    // read baseline current
    ch0 = 0;
    for(sample_count = 0; sample_count < 16; sample_count++)
    {
        ch0 = ch0 + adc_read(0);
    }
    ch0 = ch0 / 16;

    // Determine tolerance for motor current
    if (ch0 < BASE_I_LIMIT)
    {
        tolerance = LOW_TOLERANCE;
    }
    else
    {
        tolerance = THRESHOLD_SCALE * ch0;
    }

    ch0_previous = ch0; // remember last value for ch0
    sampling = 1;      // start sampling in interrupt routine
    second_timer = 20; // start timer for timeout

    // NOTE: ISR collects 1 sample for each channel and signals via adc_flag
    do
    {
        // wait for one sample to be taken for each channel
        while(adc_flag == 0);
        adc_flag = 0;
        if (collecting_data == 0)
        { // check for start
            if (ch0 > tolerance)
            {
                collecting_data = 1;
                sample_count = 0;
                samples[sample_count++] = ch0_previous;
                samples[sample_count++] = ch0;
                second_timer = 10; // reset timer to more than 6 seconds
                lcd_clear();
                lcd_puts(" Sampling data");
                lcd_goto_rc(1,1);
            }
        }
    }

```

```

        ch0_previous = ch0; // remember last value for ch0
        ch1_previous = ch1; // remember last value for ch1
    }
    else // collect data
    {
        // check relay current
        if (abs(ch1 - ch1_previous) > ch1_max_diff)
        {
            ch1_max_diff = abs(ch1 - ch1_previous);
            relay_time = sample_count; // remember time index
        }
        ch1_previous = ch1; // update last value for ch1
        samples[sample_count++] = ch0; // store data
        if (sample_count == MAX_SAMPLES)
        {
            sampling = 0; // turn off sampling in ISR
        }
        if (sample_count % 25 == 0)
        {
            lcd_putchar('.');
        }
    }
} while(sampling && second_timer && key_value != CANCEL);

// if sampling is not off then data not collected or user has cancelled
// so display message
if (sampling != 0)
{
    sampling = 0; // turn off sampling
    relay_time = -1; // reset relay_time to indicate no valid data
    lcd_clear();
    if (key_value == CANCEL)
    { // user cancelled
        lcd_puts(" Analysis cancelled");
    }
    else
    {
        lcd_puts(" Analysis timed out");
    }
    wait_or_key(5);
}
return (relay_time);
}

/*****
find_end
Identifies the samples[] array index that contains the last door motor
data point. This value is returned as an integer.

Author: Simon Perkin, November 2000
*****/
int find_end(void)
{
    int ival;
    int tolerance; // Data value defining limit for detection of data end point

    if (samples[MAX_SAMPLES - 1] < BASE_I_LIMIT)
    {
        tolerance = LOW_TOLERANCE;
    }
    else
    {
        tolerance = THRESHOLD_SCALE * samples[MAX_SAMPLES - 1];
    }

    for(ival = MAX_SAMPLES - 1; ival >= 0; ival--)
    {
        if (samples[ival] > tolerance)
        {
            return (ival + 1); // take previous position
        }
    }
    // Something wrong

    return(MAX_SAMPLES); // End of data not found
}

/*****
Door_action

Determines door action from interlock value or from user input.
Displays door interlock % and derived door direction for confirmation purposes (allows
operator to spot if interlock incorrectly detected).

```

```

    Author: Simon Perkin, November 2000
    *****/
void door_action(void)
{
    BYTE detect_interlock;

    // if interlock detection turned off, set interlock to zero.
    detect_interlock = read_seeprom(12);
    if(detect_interlock == 0)
    {
        rec.interlock = 0;
    }

    // if interlock occurred after 50% of motor activation time
    if ( rec.interlock > 50)
    {
        rec.door_action = DOOR_CLOSING;
    }
    else
    {
        rec.door_action = DOOR_OPENING;
    }

    //if no interlock was detected then interlock is zero; so ask user
    if (rec.interlock == 0)
    {
        char ch;
        rec.door_action = DOOR_OPENING; //assume door has opened
        lcd_clear();
        lcd_puts(" Door is now open?");
        lcd_goto_rc(1,0);
        lcd_puts(" Press ENT or ->");
        do
        {
            ch = getkey();
            if (ch == NEXT)
            {
                if (rec.door_action == DOOR_OPENING)
                {
                    rec.door_action = DOOR_CLOSING;
                    lcd_goto_rc(0,0);
                    lcd_puts(" Door is now closed?");
                }
                else
                {
                    rec.door_action = DOOR_OPENING;
                    lcd_goto_rc(0,0);
                    lcd_puts(" Door is now open? ");
                }
            }
        } while (ch != SELECT);
    }
    else // added 30.04.2001 to display result of interlock detection
    {
        lcd_clear();
        if (rec.door_action == DOOR_OPENING)
        {
            sprintf(lcd_buf, " Interlock: %bu%%", rec.interlock);
            lcd_puts(lcd_buf);
            lcd_goto_rc(1,0);
            lcd_puts(" Door is now open");
            wait_or_key(5);
        }
        else
        {
            sprintf(lcd_buf, " Interlock: %bu%%", rec.interlock);
            lcd_puts(lcd_buf);
            lcd_goto_rc(1,0);
            lcd_puts(" Door is now closed");
            wait_or_key(5);
        }
    }
}

/*****
analyse_door_error

Normalises the raw data (on the fly) and compares it to the
motor data describing a good door. Calculates total error.

Author: Simon Perkin, November 2000
*****/
void analyse_door_error(int last_val)
{

```



```

int sample_count = 0;
float step = 100.0/last_val;
float total = 0.0;
float sum, sum1, sum2, sum3;
int av_count, count, min;
BYTE av_data[3];
float imp1=1.0, imp2=1.0, imp3=1.0;

// set zone 1 and 2 ends + importance factors depending on door action
if( rec.door_action == DOOR_OPENING)
{
    zone1end = OPEN_ZONE1END;
    zone2end = OPEN_ZONE2END;
    imp1 = OPEN_IMP1;
    imp2 = OPEN_IMP2;
    imp3 = OPEN_IMP3;
}
else
{
    zone1end = CLOSE_ZONE1END;
    zone2end = CLOSE_ZONE2END;
    imp1 = CLOSE_IMP1;
    imp2 = CLOSE_IMP2;
    imp3 = CLOSE_IMP3;
}

// Do start section
av_data[0] = (samples[0] * SCALE_FACTOR) / I_GRID_MAX;
sum = 0.0;
av_count = 0;
while(total < 1.0)
{
    sum += samples[sample_count++];
    av_count++;
    total = total + step;
}
sum = sum / av_count;

av_data[1] = (sum * SCALE_FACTOR) / I_GRID_MAX;

min = 9999;
if (abs(av_data[0] - good_data[rec.door_action][0]) < min)
{
    min = abs(av_data[0] - good_data[rec.door_action][0]);
}
if (abs(av_data[1] - good_data[rec.door_action][0]) < min)
{
    min = abs(av_data[1] - good_data[rec.door_action][0]);
}
if (abs(av_data[0] - good_data[rec.door_action][1]) < min)
{
    min = abs(av_data[0] - good_data[rec.door_action][1]);
}
rec.zlmax_err = min;
rec.zl_err = min;

// Do middle section
for(count = 1; count < 99; count++)
{
    sum = 0.0;
    av_count = 0;
    while( total < (float)(count + 1))
    {
        sum += samples[sample_count++];
        total += step;
        av_count++;
    }
    sum = sum / av_count;
    av_data[2] = (sum * SCALE_FACTOR) / I_GRID_MAX;

    // Calc errors and find minimum error
    min = 9999;
    if( abs(av_data[0] - good_data[rec.door_action][count]) < min )
    {
        min = abs(av_data[0] - good_data[rec.door_action][count]);
    }
    if( abs(av_data[1] - good_data[rec.door_action][count]) < min )
    {
        min = abs(av_data[1] - good_data[rec.door_action][count]);
    }
    if( abs(av_data[2] - good_data[rec.door_action][count]) < min )
    {
        min = abs(av_data[2] - good_data[rec.door_action][count]);
    }
}

```

```

        if( abs(av_data[1] - good_data[rec.door_action][count - 1]) < min )
        {
            min = abs(av_data[1] - good_data[rec.door_action][count - 1]);
        }
        if( abs(av_data[1] - good_data[rec.door_action][count + 1]) < min )
        {
            min = abs(av_data[1] - good_data[rec.door_action][count + 1]);
        }

        // update max error and running totals
        if (count < zonelend)
        {
            rec.z1_err += min;
            if (min > rec.z1max_err)
            {
                rec.z1max_err = min;
            }
        }
        else
        {
            if (count < zone2end)
            {
                rec.z2_err += min;
                if (min > rec.z2max_err)
                {
                    rec.z2max_err = min;
                }
            }
            else
            {
                rec.z3_err += min;
                if (min > rec.z3max_err)
                {
                    rec.z3max_err = min;
                }
            }
        }
        // update
        av_data[0] = av_data[1];
        av_data[1] = av_data[2];
    } // end middle section

    // do end section
    min = 9999;
    if (abs(av_data[2] - good_data[rec.door_action][99]) < min)
    {
        min = abs(av_data[2] - good_data[rec.door_action][99]);
    }
    if (abs(av_data[2] - good_data[rec.door_action][98]) < min)
    {
        min = abs(av_data[2] - good_data[rec.door_action][98]);
    }
    if (abs(av_data[1] - good_data[rec.door_action][99]) < min)
    {
        min = abs(av_data[1] - good_data[rec.door_action][99]);
    }
    rec.z3_err += min;
    if (min > rec.z3max_err)
    {
        rec.z3max_err = min;
    }

    // Calc size of good data and round up average error
    sum1 = 0.0;
    for ( count = 0; count < zonelend; count++)
    {
        sum1 += good_data[ rec.door_action][count];
    }
    rec.z1av_err = (UINT) ((float)rec.z1_err/(zonelend) + 0.5);
    rec.z1_err = (UINT) ( ((float)rec.z1_err * 100.0)/sum1 + 0.5);

    sum2 = 0.0;
    for ( count = zonelend; count < zone2end; count++)
    {
        sum2 += good_data[ rec.door_action][count];
    }
    rec.z2av_err = (UINT) ((float)rec.z2_err/(zone2end - zonelend) + 0.5);
    rec.z2_err = (UINT) ( ((float)rec.z2_err * 100.0)/sum2 + 0.5);

    sum3 = 0.0;
    for ( count = zone2end; count < 100; count++)
    {
        sum3 += good_data[rec.door_action][count];
    }

```

```

rec.z3av_err = (UINT) ((float)rec.z3_err/(100 - zone2end) + 0.5);
rec.z3_err = (UINT) (((float)rec.z3_err * 100.0)/sum3 + 0.5);

// Calc total error
rec.total_error = ((imp1 * rec.z1_err * sum1) + (imp2 * rec.z2_err * sum2) +
                   (imp3 * rec.z3_err * sum3)) / (sum1 + sum2 + sum3);
}

/*****
calc_parameters

Calculates the maximum, mean, modified mean and sum for each
of the 3 zones based upon the raw data in samples array.

Author: Simon Perkin, November 2000
*****/
void calc_parameters(int end)
{
    int temp;
    long int isum;
    int imax;
    int i, j;

    // first pass
    // scale zonelend to raw data index
    temp = zonelend * end / 100;
    isum = 0L;
    imax = 0;
    for(i = 0; i < temp; i++)
    {
        if(samples[i] > imax)
        {
            imax = samples[i];
        }
        isum += samples[i];
    }
    rec.z1_imax = imax;
    rec.z1_isum = (UINT) (isum / SCALE_SUM);
    rec.z1_imean = isum / temp;

    temp = zone2end * end / 100;
    isum = 0L;
    imax = 0;

    // carry on from end of zone 1
    for( ; i < temp; i++)
    {
        if(samples[i] > imax)
        {
            imax = samples[i];
        }
        isum += samples[i];
    }
    rec.z2_imax = imax;
    rec.z2_isum = (UINT) (isum / SCALE_SUM);
    rec.z2_imean = isum / (temp - (zonelend * end / 100));

    isum = 0L;
    imax = 0;

    // carry on from end of zone 2
    for ( ; i <= end; i++)
    {
        if(samples[i] > imax)
        {
            imax = samples[i];
        }
        isum += samples[i];
    }
    rec.z3_imax = imax;
    rec.z3_isum = (UINT) ( isum / SCALE_SUM);
    rec.z3_imean = isum / (end - temp); // temp is end of zone 2

    // Second pass
    temp = zonelend * end / 100;
    isum = 0L;
    j = 0;
    for(i = 0; i < temp; i++)
    {
        if(samples[i] > rec.z1_imean)
        {
            isum += samples[i];
            j++;
        }
    }

```

```

    }
    if(j == 0)
    {
        rec.z1_imod_mean = rec.z1_imean;
    }
    else
    {
        rec.z1_imod_mean = (UINT) (isum / j);
    }

    temp = zone2end * end / 100;
    isum = 0L;
    j = 0;
    for( ; i < temp; i++)
    {
        if(samples[i] > rec.z2_imean)
        {
            isum += samples[i];
            j++;
        }
    }
    if(j == 0)
    {
        rec.z2_imod_mean = rec.z2_imean;
    }
    else
    {
        rec.z2_imod_mean = (UINT) (isum / j);
    }

    isum = 0L;
    j = 0;
    for( ; i <= end; i++)
    {
        if(samples[i] > rec.z3_imean)
        {
            isum += samples[i];
            j++;
        }
    }
    if(j == 0)
    {
        rec.z3_imod_mean = rec.z3_imean;
    }
    else
    {
        rec.z3_imod_mean = (UINT) (isum / j);
    }
}

/*****
calc_result

Uses rec.total_error value to determine the door classification using a fuzzy logic approach.
Confidence levels are assigned to each results contained in the result[] array, where
result[0] refers to GOOD classification, result[1] refers to FAIR classification and
result[2] refers to BAD classification.

Author: Simon Perkin, December 2000

15.03.2001 S. Perkin
- Maximum confidence output set to max_confidence.
- Max_confidence set to 95 to avoid implication of 100% confidence.
*****/
void calc_result(void)
{
    BYTE count;
    float confidence;
    // Max [%] confidence to be defined based upon analysis
    float max_confidence = 99;

    for (count = 0; count < 3; count++)
    {
        // Confidence level minimum
        if(rec.total_error < membership[count][0] || rec.total_error >
            membership[count][3])
        {
            rec.result[count] = 0;
        }
        else
        {
            // Confidence level ascending
            if ( rec.total_error >= membership[count][0] &&
                rec.total_error < membership[count][1] )

```

```
        {
            confidence = (membership[count][1] - rec.total_error) /
                (membership[count][1] - membership[count][0]);
            confidence = 1.0 + exp(10.0 * (confidence - 0.5));
            confidence = 1.0 / confidence;
            rec.result[count] = max_confidence * confidence;
        }

        // Confidence level maximum
        if ( rec.total_error >= membership[count][1] &&
            rec.total_error < membership[count][2] )
        {
            rec.result[count] = max_confidence;
        }

        // Confidence level descending
        if(rec.total_error >= membership[count][2] && rec.total_error <
            membership[count][3])
        {
            confidence = 1.0 - (membership[count][3] - rec.total_error)
                / (membership[count][3] - membership[count][2]);
            confidence = 1.0 + exp(10.0 * (confidence - 0.5));
            confidence = 1.0 / confidence;
            rec.result[count] = max_confidence * confidence;
        }
    }
}
```

## 17.8 Appendix H: Door Analysis Tool theoretical testing results

This appendix contains the results for the nine theoretical tests, as described in section 11. The shaded parameters facilitate the correct identification of each simulated fault.

Parameter	Tests								
Test ID	1	2	3	4	5	6	7	8	9
Door motion <sup>8</sup>	0	1	0	0	0	0	0	0	0
Motor time [s]	4.52	4.80	4.38	4.58	4.58	4.58	4.9	4.1	4.60
Good confidence [%]	99	0	98	99	4	0	99	72	0
Fair confidence [%]	0	0	0	0	94	98	0	26	0
Bad confidence [%]	0	99	0	0	0	0	0	0	99
Total error [%]	5	55	10	8	14	20	6	12	26
Z <sub>1</sub> error [%]	10	32	8	12	30	9	6	20	54
Z <sub>2</sub> error [%]	3	59	9	6	4	73	13	10	8
Z <sub>3</sub> error [%]	6	156	26	11	8	9	9	12	13
Z <sub>1</sub> mean error [%]	3	9	2	4	9	3	2	6	16
Z <sub>2</sub> mean error [%]	0	6	1	1	0	8	1	1	1
Z <sub>3</sub> mean error [%]	2	43	7	3	2	3	2	3	4
Z <sub>1</sub> max error [%]	11	42	8	10	33	9	8	22	66
Z <sub>2</sub> max error [%]	2	29	8	8	1	12	11	11	7
Z <sub>3</sub> max error [%]	5	98	54	54	12	12	12	26	26
Z <sub>1</sub> I max [mA]	3779	1657	3779	3779	3779	3779	3779	3779	4572
Z <sub>2</sub> I max [mA]	1040	2172	1040	1040	1040	1782	1040	895	874
Z <sub>3</sub> I max [mA]	3273	6186	3942	3273	3273	3273	3273	3273	3637
Z <sub>1</sub> I mean [mA]	1386	932	1423	1635	2014	1418	1306	1494	2072
Z <sub>2</sub> I mean [mA]	515	795	534	512	507	1049	546	480	554
Z <sub>3</sub> I mean [mA]	1362	4150	1965	1367	1367	1367	1254	1445	1213
Z <sub>1</sub> I mod. Mean [mA]	2453	1289	2495	2548	2812	2458	2282	2495	3598
Z <sub>2</sub> I mod. Mean [mA]	639	1447	659	642	637	1230	659	622	659
Z <sub>3</sub> I mod mean [mA]	3085	5422	3376	3085	3085	3085	3085	3085	3234
Z <sub>1</sub> I sum [A]	90.28	64.40	89.75	107.96	133.06	93.60	92.87	88.14	136.82
Z <sub>2</sub> I sum [A]	48.0	78.91	48.29	48.29	47.90	98.83	54.74	40.48	52.64
Z <sub>3</sub> I sum [A]	92.68	298.83	129.69	94.43	94.43	94.43	92.87	89.70	83.74

<sup>8</sup> 0 = opening door, 1 = closing door