Developing an Evaluation Framework for Screen Doors on Railway Platforms

By

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Declaration of Authorship

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Abstract

Platform Screen Doors (PSDs) are physical barriers installed at the edges of platforms in train stations. Such doors are widely used in modern metro stations and some heavy rail stations despite the installation cost being high. The decisions for installing these doors are made for different reasons in different systems, often without a full consideration of the relevant factors. In this thesis, there is a brief discussion around safety decision making in railway and other industries, but the main feature of this research is around the breadth of factors that can be taken into account in a conventional Cost-Benefit Analysis (CBA).

The author compiles a comprehensive list of factors associated with PSDs and develops a model to support issue identification and decision-making by project sponsors. He highlights the state-of-the-art deployment situation of PSDs and draws evidence from prominent railway systems. This thesis identifies 85 railway operations and technical factors which are affected by PSDs; compiled from sources including relevant literature, consultation with industry experts and through adoption of systems thinking. The factors are brought together to produce a system dynamics model identifying causality between the factors and succeeding variables. The factors are then quantified in their respective units using mathematical equations developed through this research, and converted into a common unit of currency. These values are incorporated into an executable spreadsheet model developed for the purpose of carrying out an economic analysis to reveal the overall gain or loss (in terms of benefits and disbenefits) associated with PSD deployment.

The model, which serves as a decision-making support tool, can be used on different rail networks to help decision makers make informed decisions when considering the deployment of PSDs. The methodology of this thesis can serve as a framework for systems engineers and can be used for other elements of a system, whereas the

models produced provide consultants, contractors and suppliers of PSDs with a comprehensive checklist that would be useful for any PSD case irrespective of the network characteristics.

To test the executable model, a case study was developed using a hypothetical station formed from a combination of real data secured from different rail systems in different continents. The data was aggregated in such a manner that stakeholder confidentiality of data is preserved. The blended real data is used to form default values in the model that can be used in cases where local data is unavailable, for example in the case of new-build platforms. Variations in local factors, e.g., the value of avoiding a fatality, cost of equipment etc., mean that it will always be recommended that the model is used to undertake a specific local evaluation both for new-build and retrofit cases. The results obtained using default values for a specimen station yielded an overall benefit of nearly £11.5 million, overall disbenefit of £11.8 million, Net Present Value (NPV) of -£271,461 and Benefit–Cost Ratio (BCR) of 0.98. This is calculated over a 35-year lifetime for the PSDs. Even though different organisations may have different BCR requirements or rules of thumb, the 0.98 BCR means that the benefits derived are just less than the disbenefits/costs involved. However, sensitivity analysis shows that small changes in input variables can change the BCR significantly, either up or down. From this generic analysis the we can reach two preliminary findings – that benefits and costs can be broadly in balance, and that it is essential that local parameters are used to support any decisions to implement or not to implement PSDs.

The high-level factors influencing the results include the value of a fatality avoided, safety (including suicides) having the greatest impact and amounting to nearly £7 million over the PSD lifetime. This is followed by energy consumption, for which a benefit of £4.3 million was determined. On the negative side, the effect on capacity leads, with a loss of £5.6 million, followed by the cost of PSD equipment that ranges from £13,000 to £18,000 per linear metre.

Application of the *Pareto principle* when evaluating the economics for one platform to a station, line or network suggests a strategic analysis and selecting only those platforms/stations with critical requirements to be fitted with PSDs. This makes the calculation much more feasible for PSD installation on those critical platforms.

The thesis therefore presents a comprehensive approach to evaluating situations, identifying relevant factors, quantifying them and coming up with evidence-based information that serves as a decision-making support mechanism which helps decision makers to make informed, scientifically based, decisions. Even though the case study presented in the thesis is around the deployment of PSDs, the framework developed can be customised to suit other scenarios for which scientifically based decision-making is required.

"...above all endued with knowledge is One more knowing."

Surah Yusuf [12:76]

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List of Acronyms and Abbreviations

ALARP	**A**s **L**ow **A**s is **R**easonably **P**racticable
APG	**A**utomatic **P**latform **G**ate
APM	**A**utomated **P**eople **M**over
ASD	**A**utomatic **S**liding **D**oor
ASPR	**A**nnual **S**afety **P**erformance **R**eport
ATP	**A**utomatic **T**rain **P**rotection
BCR	**B**enefit-**C**ost **R**atio
BRT	**B**us **R**apid **T**ransit
CBA	**C**ost-**B**enefit **A**nalysis
CLD	**C**ausal **L**oop **D**iagram
CO_2	**C**arbon di**o**xide
CSM	**C**ommon **S**afety **M**ethod
CSM-RA	**C**ommon **S**afety **M**ethod for **R**isk Evaluation and **A**ssessment
DAG	**D**irected **A**cyclic **G**raph
dB	**D**eci**b**el
DCR	**D**oor **C**ontrol **R**oom
DD	**D**river's **D**oor
EED	**E**mergency **E**gress **D**oor
ERM	**E**mergency **R**elease **M**echanism
FDS	**F**ire **D**ynamic **S**imulator
FP	**F**ixed **P**anel
FWI	**F**atalities and **W**eighted **I**njuries
GBP	**P**ounds sterling
GoA	**G**rade **o**f **A**utomation
HSR	**H**igh **S**peed **R**ail
HVAC	**H**eating, **V**entilation and **A**ir **C**onditioning

ID	**I**nfluence **D**iagram
IT	**I**nformation **T**echnology
JLE	**J**ubilee **L**ine **E**xtension
LCD	**L**iquid **C**rystal **D**isplay
LCH	**L**ost **C**ustomer **H**ours
LCP	**L**ocal **C**ontrol **P**anel
LED	**L**ight-**E**mitting **D**iode
LRT	**L**ight **R**ail **T**ransit
LUL	**L**ondon **U**nderground **L**imited
Maglev	**Mag**netic **Lev**itation
MGF	**M**echanical **G**ap **F**iller
MIT	**M**assachusetts **I**nstitute of **T**echnology
MRT	**M**ass **R**apid **T**ransit
MTR	**M**ass **T**ransit **R**ailway
NIHL	**N**oise-**I**nduced **H**earing **L**oss
NO_x	**N**itrogen **O**xides
NPV	**N**et **P**resent **V**alue
OLE	**O**verhead **L**ine **E**quipment
PED	**P**latform **E**dge **D**oor
PM	**P**articulate **M**atter
PSD	**P**latform **S**creen **D**oor
PSG	**P**latform **S**afety **G**ate
PTI	**P**latform-**T**rain **I**nterface
RF	**R**adio **F**requency
RMT	National Union of **R**ail, **M**aritime and **T**ransport Workers
Rn	**R**ado**n** (level)
RSSB	**R**ail **S**afety and **S**tandards **B**oard (UK)
SafeFITS	**Safe** **F**uture **I**nland **T**ransport **S**ystems
SCS	**S**ignalling **C**ontrol **S**ystem

SD	**S**ystem **D**ynamics
SEM	**S**tructural **E**quation **M**odelling
SFAIRP	**S**o **F**ar **A**s **I**s **R**easonably **P**racticable
SFD	**S**tock and **F**low **D**iagram
SMRT	**S**ingapore **M**ass **R**apid **T**ransit
SWR	**S**South **W**estern **R**ailway
T&W	**T**yne **&** **W**ear
tph	**T**rains **p**er **H**our
TR	**T**ons of **R**efrigeration
UK	**U**nited **K**ingdom
UNECE	**U**nited **N**ations **E**conomic **C**ommission for **E**urope
US	**U**nited **S**tates
V&V	**V**erification **&** **V**alidation
VPF	**V**alue of **P**reventing a **F**atality
VPSD	**V**ertical **P**latform **S**creen **D**oor
VSL	**V**alue of **S**tatistical **L**ife
WHO	**W**orld **H**ealth **O**rganization
WTL	**W**orkforce **T**ime **L**ost

. . . Dedicated to Hajiya
Ummulkhairi Tijjani Usman, and
Alhaji Tasiu Abdurrahman.

Chapter 1

Introduction

1.1 Background

Platform screen doors (PSDs) refer to the automated door systems used in modern metro stations and some other stations, to serve as a barrier between the platform edge and the track area of a station platform. These doors are generally configured to always be closed and only open upon arrival of a train, enabling an enhanced safety and prevention of suicide (Anderson and Harris, 2007). The door system consists of both mechanical and electrical parts, the mechanical being the door structure and door motor drive system and the electrical being the power, control and monitoring systems (Wei *et al.*, 2012).

Qu and Chow (2012) classified two different types of PSD being used in various stations across the globe, full-height and half-height or low-height PSDs. In addition to that, simple platform barriers are also used in some stations, mainly for the purpose of enhancing safety. Full-height PSDs are of two types: one which is flush with the platform ceiling, providing complete separation of the platform from the track area, usually simply referred to as full-height PSDs; and one which goes beyond head height but is not connected with the ceiling, often referred to as *platform edge doors* (PEDs), which leave a space between the two environments, enabling exchange of ventilation and noise. Half-height PSDs vary in terms of height. Some are up to the average chest height, whereas some are relatively lower, often termed *platform safety gates* (PSGs). The PSD types are further discussed in sections 1.1.1 and 4.3.

In this thesis, I present information regarding PSDs, I study the current use of PSDs, investigate their impact on the overall rail system and provide models that can aid the decision making on whether to install PSDs through economic analysis. The framework developed can be applied to other domains as well.

1.1.1 PSDs in the Global Context

Globally, there is considerable interest in continuing the development of metro and urban rail systems, as observed by Anderson and Harris (2007). Infrastructure is one area that engineers are still working on, to improve the quality of service with regard to mass transit. PSDs are an element belonging to the infrastructure considerations gaining more attention around the world; they are being installed in new stations and retrofitted into existing (mostly) metro stations and other non-metro stations as discussed in Chapter 4.

Steel platform doors were first installed in 1971/1972 in 10 metro stations along the Saint Petersburg metro line 2 in Russia (Metrobits, 2020; Wikiwand, 2020). In 1987, the idea of platform doors was adapted in Singapore but using *glass* instead of steel for underground metro stations (Zhou *et al.*, 2010). Since then, many countries have started using them and their use is now growing fast across the globe, especially in newly built metro stations. Countries having PSDs now include China, France, Hong Kong, Japan, Malaysia, Russia, Singapore, Spain, Taiwan, the United Kingdom (UK) and the United States (US).

In addition to metro stations, PSDs have some non-metro applications, i.e., they are widely used in airport systems where Automated People Movers (APMs) are in operation (example in Appendix C.5), and also on some high-speed train lines, such as parts of the Shinkansen in Japan.

While emerging designs for new metro lines often include provision for PSDs, there is little or no academic work looking at the justification for these systems, and no holistic work considering the circumstances in which fitment is justified or otherwise. The big issue here is what criteria can be adopted to enable an assessment to come to the conclusion of whether PSDs are beneficial, considering the various station conditions, and how that conclusion can be justified.

1.1.2 Engineering Configuration

The engineering configuration of the PSDs is such that it spans the entire length of the platform and contains panels that are fixed on the platform and other panels that allow for passenger exchange between the platform and the train (the doorways). Both components are usually made-up of laminated toughened glass (Hong, 2017) encased in metallic frames.

The doorways are configured in such a way that whenever there is no train on the platform, the doors are in a *close* position to prevent entry from the platform to the trackside. Therefore, the doors only open when a train come to a complete stop and the signal for door opening is active.

The opening and closing of the PSDs are usually synchronised with the train doors but with a latency of a few seconds in most cases. For a train to have the right to depart, the *close* status has to be reported to ensure safety by confirming that all PSDs are closed and that there is no entrapment between the doors. Details of the operational and structural components of the PSDs is discussed in a greater detail in Chapter 4.

1.1.3 PSD Deployment

Platform doors are usually installed in modern metro stations to carry out, most importantly, a safety function, thereby preventing passengers from gaining access to the railway lines (Anderson and Harris, 2007). This prevents the danger of accidents that may occur as a result of an intrusion onto the railway track, whether deliberately (suicide), involuntarily (passenger(s) falling), due to an intentional push (murder/assault) or by simply trespassing. PSDs are also installed for other purposes which include optimisation of energy consumption by the environmental control system (Hu and Lee, 2004), platform noise mitigation (Soeta and Shimokura, 2012) and air quality improvement (Son *et al.*, 2014) among others.

It is to be noted that previous studies counted PSDs among numerous factors that can affect the dwell time of trains at stations (Barron *et al.*, 2018), which according to Anderson and Harris (2007) can create a considerable economic disbenefit to the system. This is because the PSDs can introduce a delay to the train doors opening and closing, thereby extending the total station dwell time, which leads to an impact on the overall capacity. This capacity impact is weighted in this thesis through quantification of the change in dwell time and translating that into the corresponding change in the frequency of service. This Capacity issue is usually crucial for most railways, for example it was the motivation for the Jubilee Line Extension (JLE) project; and it caused so much attention on the Tyne and Wear (T&W) Metro in the UK (see Section 5.3.10 for details on capacity estimation).

By extension, any delay in passenger flow creates more congestion at platforms which may lead to additional capacity demand for passenger facilities such as stairs and escalators, as well as additional demand for station services such as shops, travel information services, ticketing etc., (van den Heuvel and Hoogenraad, 2014).

Reducing time waste (at stations), according to Canca *et al.* (2012), helps to obtain more time-sensitive and simple periodic scheduling for trains, thereby producing an enhanced and efficient cyclic timetable at each station. On this note, Othman *et al.* (2014) and Leurent *et al.* (2012) advised that platform congestion progressively leads to trip delays, commuter discomfort and lower overall service quality standards.

There are different drivers for the fitment of PSDs in different countries. An assessment of the pros and cons of PSDs from a holistic perspective will inform those decision makers who are considering station designs in all parts of the railway world. Note that some lines that have PSDs do not have them at above ground stations or at less well-used stations, so there are limitations in most systems. There is also a concern for train homogeneity on lines fitted with PSDs due to the fact that stopping positions and door configurations vary for different trains at different platforms. Hence, a full appreciation of the benefits and disbenefits can enable planners to design for now and for the future, taking account of all the most relevant factors.

Considering the two different sides of the effects (benefits and disbenefits) caused by the deployment of PSDs at train stations, there is a need for an evidence-based study on the magnitude of the impact of each of the two categories of the aforementioned effects on the overall railway system and, in aggregate, whether and where the positive effects exceed the negative ones. Hence the need for this study.

1.2 Decision-Making Processes

Decision-making can be referred to as the process of 'identifying and choosing alternatives' from a range of options based on the goal(s), aim(s) or objective(s) that the decision-maker wants to achieve (Fülöp, 2005). It inherently implies that for a decision to be made, there should be a number of alternatives from which to choose. This ability to choose from a range of options is one of the fundamental cognitive processes of human behaviours (Wang and Ruhe, 2007).

As Koller (2019) puts it, decision-making is only required when there is a gap in knowledge about what choice to make when you have more than one option for a particular situation, i.e., there is an element of uncertainty in the consequences of making such a decision, hence the need to quantify, distribute or express these uncertainties to help make a better, informed, decision.

In industry, decision-making is usually all about money just as it is about choices. Companies want to make smart choices of (usually) whether to engage in a particular activity or project. So, it is all about a *yes* or a *no* to whatever is on the table (Koller, 2019). In a multiple option activity/project, this could be giving a *yes* to one option and a *no* to the alternative options.

Decision-making process is all about action-taking steps followed when making a decision (Nutt, 2008). These steps can generally follow the following trend; a blended extract from Candela (2020), Fülöp (2005) and Bazerman and Moore (2012):

1. Identifying and Defining the problem
2. Determining the requirements
3. Identifying and generating alternatives
4. Defining a criteria
5. Evaluating alternatives against the criteria
6. Determining and implementing the course
7. Evaluating the outcome

There are wide range of techniques or methods followed to make a decision. The choice of which technique to use depends on the specific case and the domain under which the decision would be made. But generally, the techniques for decision-making are (Candela, 2020):

1. Rational decision-making
2. Non-rational decision-making

The *rational decision* being the decision made through a formal analysis process using objective sets of data, and the *non-rational decision* being the one made based on intuition and subjectivity. These two types of decision-making are sometimes referred to as *strategic* and *intuition* decision-making processes respectively (Elbanna, 2006). Some scholars such as Wang and Ruhe (2007) are of the view that there are four categories of decision-making, adding *heuristic* and *empirical* to the list. The *heuristic* being based on scientific theories, ethics, anchoring, etc, while the *empirical* being based on experience, estimation or experiment. For the purpose of this research, the Author will use the *rational* and *non-rational* decision-making processes respectively.

1.2.1 Railway Industry Decision-Making

In the Railways, like many other engineering-related industries, decisions are usually taken based on the significance or weight of the item being decided on. If it is a minor matter, decision makers would usually use the *non-rational* approach guided by experience, guts and judgement. However, in the case of big decisions, for examples projects to be approved, the *rational* decision-making approach is usually followed through collection and analysis of data relevant to the subject in question. For example, when selecting a new railway route from one city to another, a simulation-based rational approach could be used to come up with alternatives from which to choose.

A common process that is used in other decision-making scenarios is through a Cost-Benefit Analysis (CBA). Using CBA, positive and negative components of the subject matter are being evaluated in terms of money to enable arithmetic comparison of the negatives and positives to help ascertain whether the benefits that would be achieved outweigh the cost necessary for execution. This then supports the decision-making process. However, in many scenarios, the specific aspect needs to be examined to ascertain what decision-making approach is best suited for the situation due to constraints of resources, technology, time, budget, etc., (Wang and Ruhe, 2007).

It is interesting to note that not all issues go through a formal process of proper consideration of consequences before decision-making in the railway, despite some of them being significant ones. For example, a decision-maker involved in one of the largest railway projects in one country informed the Author that the decision to install PSDs was not based on any formal process, but rather based on *intuition*. The Author feels that while this may have been a good decision, it should have been supported by an evidential case and properly investigated to enable an informed decision. This thesis provides a methodology to support future decisions of that type.

1.2.2 Decision-Making in Other Industries

On a general note, in the terms defined above, most industry decisions are *rational*. However, different industries have different ways of making such decisions. For example, in the UK water industry, preference is given to what is termed *sustainable decision-making* with high consideration of the environmental, economic and social impacts (Ashley *et al.*, 2003), in which case, there has to be some form of assessments of these impacts through data collection and processing before making any decision. The sustainability approach can be seen to fit the water industry considering the environmental impacts that any decision in such an industry could have due to the fact that it is all about an important resource (water) that needs to be managed with high sensitivity and consideration to the planet in which we live.

In the Airline industry, however, decisions are usually around on simulation-based evidencing where data is obtained on the particular case, from which a series of computer simulations would follow to feature a number of scenarios, a result of which would serve as evidence for carrying out the *evidence-based decision-making* (Mavin *et al.*, 2015).

In one of the world's largest economic sectors by revenue, the Automotive industry, decisions are usually made through what is called a 'total quality management technique' which is one form of business analytics that is used for decision-making. The business analytic approach is gaining ground and has been adapted by many organisations where Business Intelligence is used to support decision-making (Sharma *et al.*, 2014).

It is interesting to note that in government agencies, decisions are often influenced by policies, regulations, budget constraints, politics and practical implications, among other considerations. But these are sometimes affected by conflicting goals and interests of people (Elbanna, 2006).

It was mentioned in Section 1.2.1 that some of the big decisions in the Railways are based on *intuition*. Well, this is not just a railway thing. Dupont *et al.* (2012) argue that there is a concern of road safety decisions in Europe being made with insufficient considerations to evidence-based scientific approaches, despite these decisions being on safety issues, meaning they are issues that could lead to loss of lives or injuries. To this, researchers such as Dupont *et al.* (2012) and Fancello *et al.* (2015) are proposing ways via which better decisions could be made using decision support mechanisms applicable to the road safety sector. An example of these is the *Safe Future Inland Transport Systems (SafeFITS)* tool launched by the United Nations Economic Commission for Europe (UNECE) to facilitate knowledge-based decision making in road safety (Yannis *et al.*, 2018).

This demonstrates the need, in a wide range of industries, for business cases particularly around safety related decision making due to the unique nature and importance of safety. Safety-related decisions could either lead to saving lives or putting lives at risk, and do therefore compromise on other decisive factors like money in order to save lives *so far as is reasonably practicable* (SFAIRP) as highlighted in the Rail Safety and Standards Board (RSSB) guidance documents on Taking Safe Decisions (RSSB, 2019; RSSB, 2018b).

1.2.3 Where this Thesis Fits in Decision-Making

This thesis develops a holistic approach to supporting decision-making through a multi stage process which leads to a comprehensive understanding of the issues at hand and therefore facilitates making informed decisions.

The stages of the process include: identification, where all relevant factors are identified, establishing the causes and relationships existing among the factors, the magnitude of impacts on the identified factors, putting all the factors and relationships into a platform that uses a common unit of currency which then enables CBA to be conducted.

This process enables the development and exploitation of a CBA to the installation of PSDs for the first time, and thereby supports future decision-making in their use.

This comprehensive approach includes both types of decision-making mentioned in Section 1.2 into the framework; from the *rational* aspect of putting the list of factors together, which also involves some *heuristic* aspects; to the arithmetic component that involved a lot of *empirical* input.

1.3 Problem Statement

To date, there have been a few studies on the effects of PSDs on particular features of their operation or economics. For instance, dwell time was explored by Anderson and Harris (2007), Barron *et al.* (2018), and Rodríguez *et al.* (2016), the energy consumed by air conditioning systems by Hu and Lee (2004), platform air quality by Jeon *et al.* (2012), Kim *et al.* (2012), and Son *et al.* (2014), emergency evacuation time by Qu and Chow (2012) and noise pollution at train stations by Soeta and Shimokura (2012). But there seems to have been no research which brings together the overall effects of PSDs on the entire railway system, i.e. merging these individual effects and others (such as service disruption, suicide prevention, etc.) together to formulate a bigger picture, thereby making it clear whether the PSDs in aggregate have a positive or negative effect. As a result, there is no common understanding of the conditions under which it is beneficial to include them in the designs of new stations or to retrofit them into existing ones.

The author tackles this problem by identifying, evaluating and bringing together the positive and negative effects of PSDs. In addition, the research addresses the issue of whether it can be economically justifiable to retrofit PSDs on existing station platforms taking into account platform-specific characteristics. For new station designs, this thesis provides a guide to whether PSDs are worth incorporating into the designs or not.

In accordance with the rail systems surveyed, the current practice in the industry does not appear to be on any informed basis (at least for those systems)[1]. PSDs are installed or not installed based on the preference of those in charge, without substantial evidence for making a comprehensive evaluation, despite the fact that the PSD is located at the platform-train interface (PTI) which is one of the greatest sources of injuries and fatalities (Hirsch, 2008; RSSB, 2020). This is perhaps due to the lack of an established procedure or knowledge for performing such an evaluation. This thesis can help the industry fill in such a significant gap.

1.4 Objectives of the Research

The aim of this thesis is to conduct an economic analysis of the deployment of PSDs on train station platforms, by addressing the following research questions:

1. Identify the factors affected by the installation of PSDs.
2. Develop a systematic cost-benefit analysis (CBA), to evaluate the overall gain or loss in the railway system due to PSDs by:
    (a) Estimating the whole-life disbenefits associated with PSDs including, for example, the costs of purchase, installation, maintenance, etc.
    (b) Estimating the whole-life benefits derived from PSDs including, for example, safety, reduction in energy consumed by the environmental control system, etc.
    (c) Developing a methodology to determine the benefits and disbenefits and how to evaluate them.
3. Develop a model to integrate the factors identified and developed in point 2 for the potential use of decision makers and planners.
4. Develop guidance for stakeholders considering the installation of PSDs in new-build stations or retrofitting them on existing platforms.

[1] Please refer to section 4.11 for details.

1.5 Hypothesis

The hypothesis of this thesis is as follows:

There are stations and platforms for which a holistic evaluation of PSDs will show that they are justified. There are other platforms and stations for which it will never be justifiable to fit PSDs, although stakeholder decisions are not always rational. Testing this hypothesis and defining the criteria by which it is judged will enable the researcher to define the conditions for where PSDs are and are not justified.

1.6 Scope and Limitations

This thesis focuses on studying the current use of PSDs in metro systems by determining their whole-life effects on several aspects of the operation of the railway system over the PSDs' lifetime. This involves economic evaluation of these effects to inform the decision on whether to have them for a particular platform.

This is achieved via:

1. Identification of the factors that are affected by PSDs.
2. Quantifying these factors and translating them into a common unit of money.
3. Performing a CBA on the deployment of PSDs on a platform belonging to a hypothetical station formed by a combination of real data.
4. Testing the sensitivity of the resultant evaluation to the variability of identified key factors.

A limitation of this thesis is that it does not address the PSD manufacturing process or structural configuration, or the mechanism of the function, integration and operational requirements of PSDs. Also, the thesis does not provide any decisions to install the doors on particular platforms but can be used to inform and support the decision of whether or not to have them. The analysis presented can also be used to ascertain the impact of changes in certain factors and how that affects the overall assessment, e.g., how sensitive it is if the cost of PSDs were halved or doubled, etc.

PSDs can be used not only on metros, but also for bus rapid transit (BRT), light rail transit (LRT), tram systems, people movers, high speed rail (HSR) services, and other regional or mainline train services. This thesis focuses only on the deployment of PSDs for metro systems. However, the methodological framework and models can be adapted for use in other situations, with appropriate changes.

1.7 Novelty of the Research

There has been work carried out by researchers on some individual issues associated with PSDs. However, there is no published research today which addresses the combined issues together and brings in the various positive and negative components. The present research aims to do this and more by:

1. Exploring more issues associated with PSDs.
2. Valuing PSD-related issues.
3. Evaluating the combined benefits and drawbacks.
4. Providing guidance for assessment of PSD deployment.
5. Providing an extensive checklist for stakeholders involved in PSD evaluations (see Appendix E).

The thesis provides useful insights for PSDs installation both for retrofit and new build cases. It would also be useful in both cases where partial or whole-line fitting of PSDs is being considered.

1.8 Significance of this Thesis

This thesis, therefore, aims to provide support to railway stakeholders with regard to decision making to deploy PSDs on station platforms. The stakeholders likely to benefit from this thesis include:

1. Decision makers
2. Designers
3. Regulators/Approvers of system designs
4. Consultants/Contractors bidding for a PSD project
5. Manufacturers/Suppliers of the PSDs.
6. Systems Engineers

Decision makers can use the model to see the impact of the decision to install PSDs. They can also see an estimate of the financial requirements versus the benefits that would come in year after year until the end of the PSDs' lifetime. This would help them make an informed decision that would lead to channelling of resources where they are best needed, either investing in PSDs or being diverted to something else.

Designers of modern stations would benefit from having at their disposal information about PSDs, such as their functions, aesthetics, etc., a list of factors that should be considered in having PSDs, and a method for how to avoid or plan against anything that may be seen as unfavourable.

PSD manufacturers would be able to see the challenges of their product in the complex railway environment and could plan to address some of the issues discussed in this thesis, for example, better integration with the operation of the train doors to minimise the effect on dwell time, robust design to enable safer evacuation during emergencies, etc.

Systems Engineers would also find this thesis useful, particularly from a systems thinking point of view, and for the identification and modelling methodologies developed in the thesis that can be applied not only to PSDs but also to other elements belonging to a system of systems. The overall framework developed in the thesis can be applied to other domains as well.

In general, the thesis is expected to assist the rail industry by providing an extensive checklist of the many factors affected by PSDs to avoid unexpected outcome after PSD installation and to enable proper planning beforehand. Both PSD project consultants and system design approvers would likely be among the many potential beneficiaries of the extensive checklist.

1.9 Methodology

PSDs were studied in a variety of use cases which enabled the discovery of 85 factors within railway systems that are affected by the installation of PSDs. These factors were discovered using ways such as sourcing from the current literature, consultation with experts in the industry and brainstorming using a systems thinking technique.

The factors discovered were then used to develop a *System Dynamics* (SD) model showing the cause and effect relationships among the factors. Next, these factors were evaluated using mathematical models developed by the author and quantified to a common unit of money to enable a CBA.

The author then developed an executable model in the form of spreadsheets using mathematical equations. The model was developed such that it can be customised to suit any platform for which fitting of PSDs is being considered. It can be used to generate statistical results that would inform the decision of installing these doors. This can be scaled up to stations, lines and networks. The economics of scaling depend on the available data, particularly for sensitive variables such as incident records which may suggest strategically installing PSDs only at platforms/stations with certain characteristics but not on the whole system.

Details of the procedures followed for each of the steps mentioned are given in Chapter 3.

1.10 Thesis Structure

The thesis is formed of seven Chapters and is organised in the following structure:

Chapter 1 provides a preamble to the topic, giving the aim and objectives of the thesis, some basic facts about PSDs, what the current problem is, scope and limitations, significance, novelty of the research, and structure of the thesis.

A discussion of the concept of *systems theory* which underpins the research direction is presented in Chapter 2, detailing what concepts are used and how the author chose the best SD tool for PSDs. This is followed by Chapter 3 which presents the research method followed to develop the various PSD models.

Chapter 4 contains the fundamental knowledge about PSD, types, functions, etc., It presents the state-of-the-art literature and a further discussion on the identified benefits and costs/disbenefits associated with the presence of PSDs on a given platform.

The methodology presented in Chapter 3 is used and presented in Chapter 5, with details of the SD model and the mathematical modelling carried out for the elements of the SD model. Chapter 6 focuses on the generic model developed and statistical analysis carried out on a set of data used to form the characteristics of a hypothetical station.

Chapter 7 concludes the thesis with key findings, critiques and recommendations for taking the work further.

Note that this thesis has no '*Literature Review*' Chapter because the literature sources are referred to in the form of citations to support the corresponding arguments as and when appropriate.

1.11 Summary

This Chapter introduces the topic of the thesis and discusses the aim and objectives of the thesis which address the evaluation of PSD deployment on station platforms.

The Chapter also presents the structure of the thesis through a summary of what each Chapter contains.

Chapter 2 is next; it gives a background of the underpinning concept that paved the way for the thesis, namely systems theory.

Chapter 2

Systems Theory

2.1 Preamble

In this Chapter, the concept of systems theory and related topics are discussed, stating their relevance to the research and how they are used. This is important because the thesis fundamentally uses the concept of systems thinking to identify some of the factors within the railway system that are affected by PSD deployment. The overall framework developed in the thesis can also be used in similar scenarios in the systems engineering domain.

2.2 Systems Theory

Systems theory (often called systems science) is a term used to describe the interdisciplinary study of systems dealing with logic formulation for understanding relations and patterns of complex problems (Haraldsson, 2000). A system is considered to be an entity having interdependent and interrelated components in which a change in one part can have an effect on several other parts and the whole entity in general. The concept of systems theory has been derived from the famous *Aristotle's Holism* (Mele *et al.*, 2010) which promotes understanding of the whole as opposed to understanding just the parts.

The concept has gone through various developments in various fields of study and is often associated with the works of Von Bertalanffy in the 1950s who defined a system as a 'complex of interacting elements' (Mele *et al.*, 2010; Midgley and Rajagopalan, 2019). The concept of systems theory is applicable broadly to principles such as:

1. Systems engineering
2. System dynamics
3. Systems psychology
4. Systems ecology
5. Systems biology

The last three principles are not directly relevant to this study, but the first two principles are; they both come under the umbrella of systems thinking, as further discussed in the subsequent sections.

2.3 Systems Thinking

Systems thinking is a way of synthesising one's thinking towards producing a robust outcome from a combination of entities using a set of analytical skills and tools, thereby improving the understanding of the dynamics that influence a system (Heke *et al.*, 2019; Knight *et al.*, 2019). With systems thinking, one can make use of practical system ideas to address challenging and complex issues within an organisation, environment or society.

Systems thinking attributes include recognising boundaries and interrelationships existing among parts of the system in various situations. Systems thinking also involves evaluation (learning and judgement) of situations/system components from multiple perspectives with wisdom, making it *transdisciplinary* in nature (Midgley and Rajagopalan, 2019).

The systems thinking approach has been used in this thesis to clearly establish the links existing among the factors that are affected by PSDs, which led to the development of mathematical relationships that enabled the quantification of those factors.

2.3.1 Systems Engineering

Systems engineering is often defined as an interdisciplinary approach (BKCASE Editorial Board, 2014; Department of Defence, 2001) for designing and managing complex systems to enable the realisation of their success over a given lifetime (Fraser and Gosavi, 2010; Haskins, 2006). To optimise complex systems, systems engineering employs various work processes such as system dynamics modelling, systems architecture development, requirements management and the processes of verification and validation (V&V) through a life-cycle of the project/product.

2.3.2 System Dynamics

System dynamics (SD) refers to a graphical and mathematical modelling approach of understanding the linear and nonlinear behaviours of complex systems over time. In order to frame, understand and discuss the dynamic behaviour of complex systems, SD makes use of stocks (accumulators), internal feedback loops, flows, time delays and table functions.

SD was first created at the Massachusetts Institute of Technology (MIT) by Professor Jay Forrester, in the mid-1950s (Forrester, 1995; Ossimitz, 2000; Toole, 2005). Forrester started with hand calculations (or simulations) of the stock-flow-feedback structure of a company, and developed the process to the level of formal computer modelling, leading to the present-day SD (Radzicki and Taylor, 2008). SD usually employs causal diagrams, often referred to as *SD tools*, to deal with issues and problems associated with dynamic entities. However, there are scenarios where stand-alone arithmetic equations are used to reveal the dynamic nature of systems.

2.4 System Dynamics Diagramming Techniques

The term SD tool is used to represent a graphical tool that makes it possible to visualise causal relationships between different variables of a system (Zolfaghari and Blumenfeld, 2016), thereby acting as a diagnostic tool for these variables based on the concept of systems thinking (Toole, 2005).

SD tools are used to understand the behaviour of complex systems through model development (Brunton *et al.*, 2019) such that variables are represented with nodes and connected by arrows (links), showing the direction of the effect. The Author has therefore found it necessary to use this diagramming technique to depict the causal relationships among the identified PSD factors. Examples of the most common SD tools include:

1. Path analysis diagrams
2. Ishikawa diagrams
3. Causal loop diagrams
4. Stock and flow diagrams
5. Directed acyclic graphs
6. Influence diagrams

2.4.1 Path Analysis Diagram

Path analysis refers to a causality-focused multiple regression technique that is capable of producing structural equation modelling (SEM). It is used to establish the direct and indirect dependability of various variables in a path-chain, which can be statistically comparable.

Path analysis is mostly easy to understand and has been used in the past for abstract systems of variables covering three main domains, namely recursive SEM, deterministic linear systems (Holland, 1988) and, most recently, analysis of trends (path analysis) as featured in recent studies (Grant, 2019; Tan, 2018).

2.4.2 Ishikawa Diagram

This refers to a cause and effect diagram developed by a Japanese quality control expert Kaoru Ishikawa (1968) with the aim of showing the causes of a particular event using a fishbone style, with the fish head representing the effect and the fishbones representing the branches of the major causes. This diagramming technique has been categorised as a lower-level approach to the identification of factors such as the products, processes and requirements, etc., of a system (BKCASE Editorial Board, 2014).

The Ishikawa diagram is often called the fishbone diagram and is mainly used for root-cause analysis in manufacturing, product marketing, service industries and, recently, in the medical field (Liliana, 2016; Wong, 2011). One of the major drawbacks of the Ishikawa diagram is that it is difficult, if not impossible, to show overlap, if there is any, among the major and/or minor causes, and this is a required feature in the PSD case as further explained in section 2.5.

2.4.3 Causal Loop Diagram

Causal Loop Diagrams (CLDs) are simple maps of systems displaying all the constituent components and how they interact with each other, thereby revealing the overall structure of the system in terms of the relationships among the various variables (Zolfaghari *et al.*, 2016) which makes it possible to ascertain the behaviour of the system.

CLDs aid the qualitative analysis of a system to a minimum detail by visualising the system's structure and behaviour using variables (nodes), links (arrows) and polarities (+ and – signs). CLDs can also be used for qualitative analysis. However, for more detailed analysis, a CLD can be transformed into a stock and flow diagram (described in section 2.4.4).

2.4.4 Stock and Flow Diagram

This is a type of advanced CLD meant for visualising entities that accumulate over time (stock) and the rate of change of those entities (flow). The stock and flow diagram (SFD) is used to establish the relationship between stock and flow entities. The stock entities are referred to as those variables that are measured at a specific point in time, whereas the flow entities refer to the variables that are measured over an interval of time. Both stock and flow entities can carry mathematical equations for quantitative modelling (Bala *et al.*, 2019; De La Torre *et al.*, 2019).

2.4.5 Directed Acyclic Graphs

A Directed Acyclic Graph (DAG) is a finite directed graph with no directed cycles. A DAG has a topographical ordering which always maintains consistency in the direction of flow through connections between one preceding variable and the following one (Li and Shan, 2019). However, a DAG does not allow cycles (loops) within the network itself. A path radiating from a node within the network would never return to that particular node, hence the name *acyclic* (Evans *et al.*, 2019).

2.4.6 Influence Diagram

An Influence diagram (ID) is a compact mathematical representation of probabilistic inference and decision-making problems in a graphical form, using nodes and arrows. ID is just another form of DAG, but with various node options, namely decision, uncertainty, deterministic and value, and with various connectivity (arc) types between the nodes, namely functional, conditional and informational, mostly used to describe technical and operational subsystems. IDs are currently being used for modelling of decision-making problems and solutions (Byun and Song, 2019).

2.5 Choice of Diagramming Technique

Determining various relationships among the various factors of a given system yields a comprehensive understanding of the system itself and the emerging issues around it. Considering the various SD tools discussed and their respective features (see Table 2.1 for an extract of the features sourced from the respective sources cited under each technique in the sections above), the author has come to the conclusion that the most relevant diagramming technique to adopt for this research is the CLD. This is because it has not only the ability to visualise the relationships among various elements, but also allows overlapping of effects in any direction and without any restrictions, unlike the other tools, except for the SFD. However, the SFD has a timeline trace function which is used to determine the behaviour of an entity over a period of time. This is an extension of the CLD and is a feature that is not needed for the PSD case.

TABLE 2.1: Matrix of the Features of SD Tools (Author)

Feature / Model	Cause & Effect	Interaction	Overlap (Loop)	Equation Modelling	Total Features
Path Analysis Diagram	√	√		√	3
Ishikawa Diagram	√	√			2
Causal Loop Diagram	√	√	√	√	4
Stock & Flow Diagram	√	√	√	√	4
Directed Acyclic Graphs	√	√		√	3
Influence Diagram	√	√			2

Using a CLD enables a wide range of discussion opportunities about how the elements relate to one another, and how a change in one issue generates changes in many others, showing whether that change is positive or negative. It also simplifies the transformation of a verbal description into a feedback structure, making it suitable for visualising complex interrelations within a system.

CLD has been around for a long time and has been used by many researchers in the past (Cooper, 1980; Morecroft, 1982; Senge, 1990) as well as in recent studies (Abdurrahman *et al.*, 2018; Bala *et al.*, 2019; Zolfaghari *et al.*, 2016).

2.6 Other Relevant Phenomena

Apart from the Systems theory aspects that underpins the processes employed in this thesis, there are other relevant phenomena worth discussing, for example, the Common Safety Method (CSM) framework and the concepts of affordability and sensitivity. These are discussed in Sections 2.6.1, 2.6.2 and 2.6.3 respectively.

2.6.1 Common Safety Method

The Common Safety Method for Risk Evaluation and Assessment (CSM-RA) is a European Commission regulation which provides a mandatory framework and sets out legal obligation for the evaluation and assessment of risks associated with railway changes, with the aim of harmonising risk evaluation and assessment (ORR, 2020). These changes can either be organisational, operational or engineering changes (MMRA, 2015).

This regulation needs to he adhered to in situations where PSDs are to be retrofitted on platforms and are being deemed to be significant changes. The framework for risk evaluation and assessment needs to be followed, and an independent assessment body would have to be involved according to the CSM-RA regulation to help navigate through the stages of the framework to ensure proper risk assessment for the changes being introduced. This is mandatory for changes deemed significant (RSSB, 2017b).

2.6.2 Affordability

Affordability, according to Redman and Stratton (2000), is the 'degree to which the life-cycle cost of an acquisition program is in consonance with the long-range investment' and structure plans. Affordability id deemed obtained when three element are balanced namely, cost, performance and schedule. With reference to PSDs, these three elements have to be evaluated to ascertain whether installing the doors is affordable to the stakeholders involved. To do that evaluation, the evaluation framework developed in this thesis is crucial.

2.6.3 Sensitivities in Numbers

Sensitivity refers to the degree by which certain outcomes are influenced by the changes occurring within the contributing factors. For the PSD case, sensitivity analysis is considered for the factors analysed. These are presented in Section 6.4.3.

2.7 Summary

This Chapter has provided a theoretical background about the concept of systems theory and the underlying principles relevant to the research topic. The CLD has been identified as the most suitable SD tool for visualising the impact of PSDs on various aspects of the rail system and, accordingly, it is used to develop the PSD SD model using the method described in the next Chapter.

Chapter 3

Methodology Development

3.1 Preamble

This Chapter contains the methodology followed to identify relevant factors associated with the deployment of PSDs, individual measurements and assessments of the identified factors, formation of the SD model, and the techniques employed in quantifying these into an executable model aimed to support decision-making with regard to PSDs.

3.2 Methodology Flowchart

The basic question requiring attention regarding the deployment of PSDs is 'under what conditions would the deployment of platform screen doors be justifiable for a given platform, station, rail service line or entire rail network?'

To answer this question, various stages were followed to identify the key factors around PSD deployment that affect the railway. These stages are given in the flowchart shown in Figure 3.1, starting from identification of the issues through to the overall conclusion and advice. Various parts of the flowchart are discussed in detail in the respective sections of this thesis.

Identification of the issues or factors affected by the presence of PSDs is considered to be the first stage in answering the question. This is followed by the formation of a graphical display termed the *SD Model* (Figure 5.2) which depicts the main causes and effects around these identified issues. The causes and effects are further marked by the

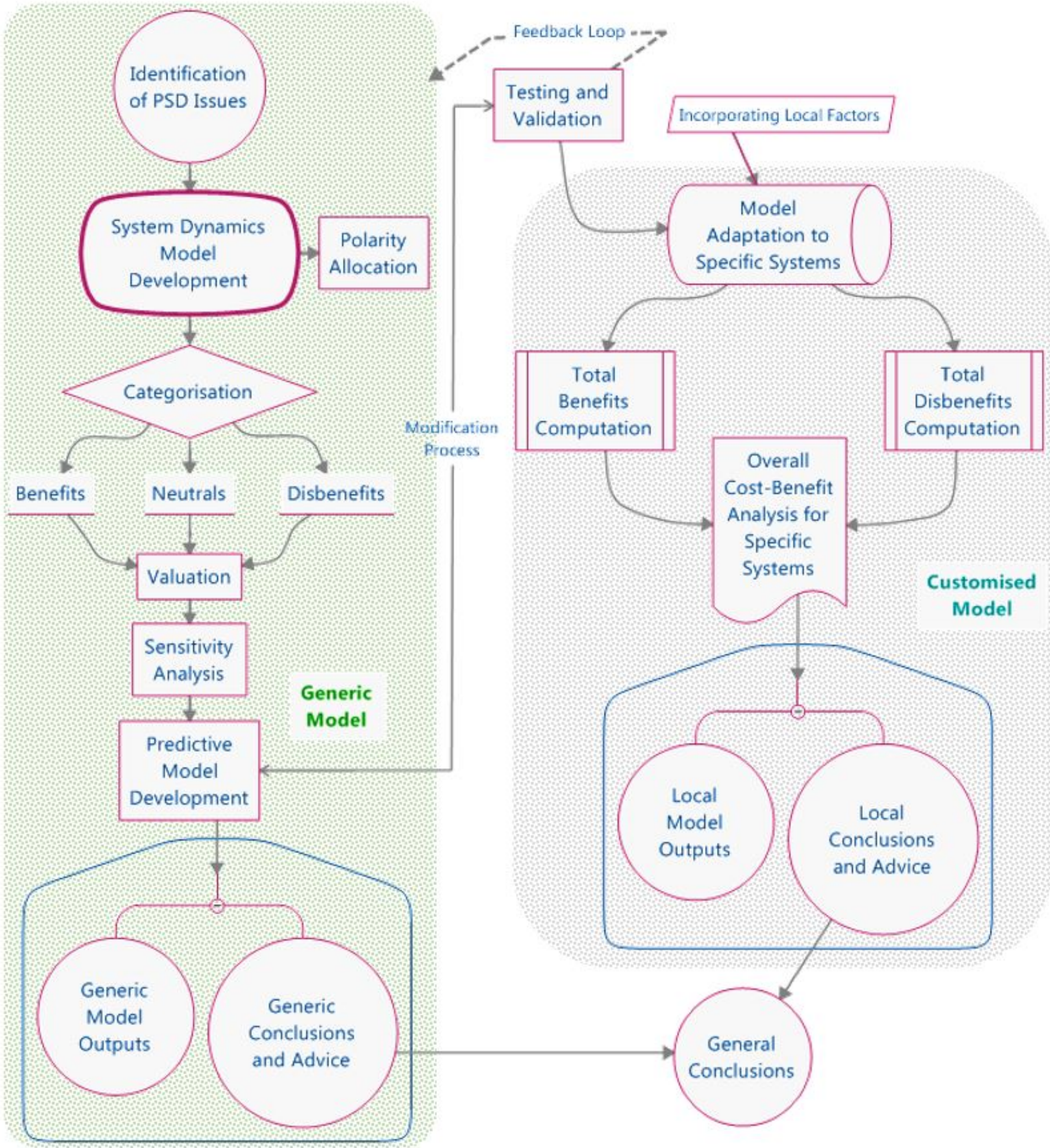


FIGURE 3.1: Methodology Flowchart (Author)

allocation of polarities among the various issues to indicate the consequent change of each resulting from a variation in the preceding variable(s).

The SD model (Figure 5.2) helps to ensure a comprehensive coverage of factors during the categorisation and valuing processes which were carried out to note and value benefits, disbenefits and neutral factors. To ascertain the significance of each factor, sensitivity analysis (details in Section 6.4.3) is paramount for clearly identifying the variables that are critical and those that may be of less significance. This is followed by the main formulation of the model that serves as a prediction tool to help answer the question with both evidence and confidence.

Model validation was carried out with a small number of experts (due to scarcity of experts in this domain) from the industry to verify its fitness for purpose in specific scenarios of PSD deployment and also led to some generic interim conclusions to be drawn that would provide appropriate advice to those parties thinking about installing PSDs (see Section 6.3.5).

3.3 Identification of PSD Issues

From early stage of the research that led to this thesis, through to the time of compilation, literature was studied to explore the status quo of issues associated with PSDs, from which various issues were discovered associated with the effects of PSDs. Tables 4.2 and 4.3 presented in Chapter 4 provide lists of the benefits and disbenefits of PSDs respectively. Although extensive, the inventory may still not be exhaustive as it is limited to those factors that could be identified and supported with evidence (using the three techniques listed below) at the point this thesis was compiled. Some of the listed items can cause further effects, for example, reliability issues of the PSDs can further cause delays (Barron *et al.*, 2018). These factors are all included in a checklist in Appendix E and indicated in Figure 5.2 which shows the relationships among the various factors.

The following techniques were used in the identification process of these factors:

1. Sourcing from the literature
2. Discussion with experts from industry and academia
3. Systems thinking and logical analogy (subsequently verified through industry experts)

3.3.1 Sourcing From the Literature

Through the literature search, numerous factors were identified as being affected by the installation of PSDs on platforms. Most literature on PSDs usually focuses on a particular factor or two but none of the available literature looks at the overall effect. For example, Lin (2016) explored how the presence of PSDs affects the Particulate Matter (PM2.5) concentrations on underground subway platforms, supporting the argument with data. This and other relevant sources were taken as credible due to the fact that they are evidence-based, peer-reviewed and could not obviously be contradicted. However, all factors from the literature were carefully considered and discussed with experts as a form of validation even though the sources were peer-reviewed. Evidence of these sources is acknowledged in various sections of this thesis, predominantly in Chapter 5 while discussing and analysing the respective factors.

3.3.2 Discussion with Experts

Not all factors that the researcher contemplated were found in the existing (published) body of knowledge. Hence, the researcher went further to identify more factors through consultation with experts in the railway domain[1]. These experts were categorised into two groups – academic experts and industry experts, as clearly captured in Figure 3.2.

The researcher undertook a series of discussions with notable people, for example Hirsch (2008) who has demonstrated a good understanding of the subject matter through various publications including Hirsch *et al.* (2007) and Kyriakidis *et al.* (2012). Others prefer to remain anonymous and come from various industry positions with experience in one or more of the areas emanating from *Industry* in Figure 3.2. Some of them are cited in various elements across the thesis.

[1]Note that the number of experts that have contributed is small. This is due to the scarcity of experts in this specific subject domain and their availability and willingness to contribute.

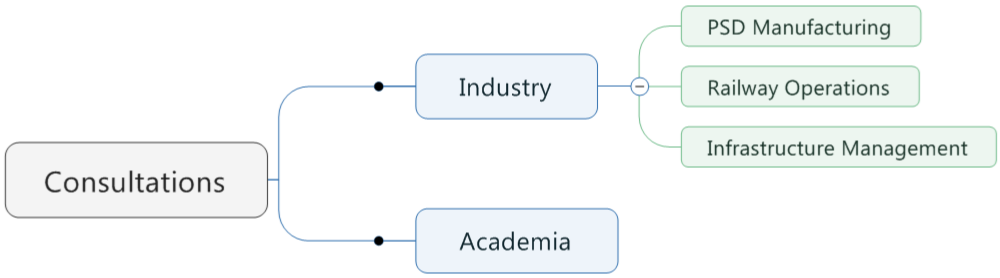


FIGURE 3.2: Consultation Sources Used by the Author

3.3.3 Systems Thinking

Some of the factors were brought to life by the author through a systems thinking process which acknowledges the various possibilities of effects on various railway components. This was made possible through the development of a CLD which depicts all the PSD causes and effects covered in this thesis (see Figure 5.2).

After the personal analysis, the listed factors were then taken for verification through the consultation processes described in Section 3.3.2.

3.4 Causal Structure Development

Causal loop diagramming is one of the system thinking tools used for the visualisation of causal relationships existing among various interrelated variables (Abdurrahman *et al.*, 2018). It makes it easier for complex systems to be understood in the shortest possible time and with the least possible effort. In CLDs, the variables are represented by nodes, and the relationship among them is represented by arrows termed 'causal links' connecting the variables.

As described in Chapter 2, CLD was chosen for this research because of its ability to overlap numerous effects among intended variables and in all directions within the causal structure. In addition to that, CLD is also capable of revealing the nature of the subsystems in the form of loops, either self-balancing or self-reinforcing (Haraldsson, 2000). It also has a verification function in the form of *causes tree* and *uses tree* diagrams. These attributes make CLD suitable for this research. The choice of CLD as the diagramming technique used in the research is explained in Section 2.5.

The main idea of the CLD for PSDs (Figure 5.2) is to depict how other aspects of the railway system and operation are affected by the deployment of PSDs on platforms. This provides a generic overview of the overall effects of PSDs on the whole railway system. The diagram was developed using the Vensim software package.

3.4.1 Vensim Software

Vensim software, developed by Ventana Systems, is a tool for the development of CLDs and has been used by researchers, including Zolfaghari and Blumenfeld (2016), to enable the development of their cause and effect diagrams. The package enables a pictorial representation with specified elements including *variables*, *levels*, *arrows*, etc.; it provides a flexible environment within which one can develop the structure and assign polarities to respective variables. This software was used for the development of an overall CLD for PSDs as shown in Figure 5.2.

3.4.2 Categorisation

All identified PSD issues were categorised by the author into one of three categories:

1. Benefits
2. Disbenefits
3. Neutral

This was done so that the big picture could be drawn for the decision to install or retrofit PSDs on a particular platform within a railway network. The aim is to evaluate the overall effects, whether positive, negative or otherwise of having PSDs.

3.4.3 Polarity Allocation

In a CLD, the direction of effect from one variable to another is assigned based on the polarity symbols (+) or (–). A plus sign means that an increase in the first variable would lead to an increase in the second/following variable, whereas a minus sign means that an increase in the first variable would lead to a decrease in the second/following variable.

It is to be noted that with causal loops, the order of polarity always starts with an increase, even if the previous step was a decrease. For instance, for the variables *Service Disruption, Delays & Cancellations, Customer Satisfaction* and *Good Service Reputation*, as shown in Figure 3.3, a change in *service disruption* leads to a change in *delays & cancellations*; therefore the two nodes are linked by an arrow pointing in the direction of change (*delays & cancellations* in this case). An increase in *delays & cancellations* will cause a decrease in *customer satisfaction*, hence the negative sign alongside the arrow pointing at *customer satisfaction*.

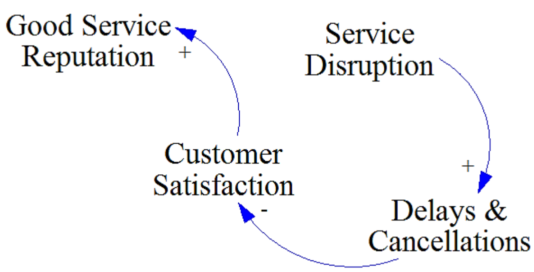


FIGURE 3.3: Polarity Allocation on a CLD (Author)

The next step would be to question what happens to *good service reputation* if *customer satisfaction* increases, even though the trend indicates that it would decrease with an increase in *delays & cancellations*. However, the question remains as to what would happen if it increases. Hence, the positive polarity of *good service reputation* means that it will increase if *customer satisfaction* increases, ceteris paribus. This enables jumping to or starting from any variable on the diagram and still being able to decipher the relationships (Love *et al.*, 1999). The changes to variables may either be qualitative or quantitative.

3.5 Valuation Process

Upon completion of the identification and categorisation processes, the issues were then taken one at a time for valuation. This simply refers to the development of mathematical equations for each factor with which it could be estimated using the evidence available for the issue in question. The full mathematical models developed for each variable are given in Section 5.3.

3.6 Model Adaptation to Specific Systems

Hypothetical station was formed to have the characteristics of the default values combined from real data taken from the various rail systems mentioned in Section 6.2.1. The model (described in Section 6.2) was run and results were generated in a way that specific systems would evaluate the economics of PSD deployment. The scenario and results are discussed in Section 6.4; the characteristics of the hypothetical station are given in Appendix B.

3.7 Summary

This Chapter provided a comprehensive guide to the various processes involved in this research, from the initial stage of identifying the factors in a railway system that are affected by PSD deployment, through to the model development processes including the SD model, mathematical models and executable model, and the various stages followed to obtain the final results.

The next Chapter provides a fundamental background and literature on the types, functions, components, benefits and disbenefits of PSDs and their interface with signalling and control systems.

Chapter 4

Platform Screen Doors

4.1 Preamble

This Chapter covers the fundamental knowledge of platform barriers, including the respective terminologies used to refer to the different types of those barriers. It also discusses the general rationale for installing barriers, and what actually drives the decision to install them (the business case). Included in the Chapter are lists of benefits and disbenefits associated with platform barriers.

4.2 Platform Barriers

Platform barriers refer to physical structures installed between the station platform edge and the rail track (Ramasearmy, 2017), usually along the full length of the platform (Deegan *et al.*, 2015), with dedicated doorways for boarding and alighting. Modern platform barriers are usually made up of laminated toughened glass (Hong, 2017) encased in metal frames. However, there are certain types of platform barriers that are merely made of metal bars without the glass component. The general perception regarding platform barriers relates to keeping passengers away from the platform edge, but there are more factors to consider, as discussed in various sections of this Chapter.

4.3 Types and Terminologies of Platform Barriers

There are currently many types of platform barriers that are used for many purposes. The choice of which barrier to install depends largely on the purpose it is intended to serve, and the funds available for it. So, it is generally purpose and cost that influence the choice of which of the platform barrier types to deploy. Images are reproduced in Appendix C for each of the door types mentioned below.

Platform barriers are called many different names, some of which relate to their height or structure. However, the most common name is ***Platform Screen Doors (PSDs)*** which can most of the time be used to refer to any form of platform barrier (as is the case in this thesis), even though it is probably one of the only two names used to refer to floor-to-ceiling *full-height doors* that are operated automatically on opening or closing of the train doors, the other being *Hermetic PSDs*.

Another term is ***Platform Edge Doors (PEDs)***, a synonym to PSDs but mostly used when referring to doors that are full height [around 2.5 metres tall (Deegan *et al.*, 2015)] but do not have an air seal at the ceiling level of the doors. Hence, they do not completely isolate the platform in terms of ventilation but allow exchange of air between the platform and trackside (or tunnel as the case may be). These are also known as *Semi-hermetic PSDs* such as those seen on the Jubilee Line in London (see Appendix C.3).

Both Hermetic PSDs and PEDs have a similar height range except for the air seal in hermetic PSDs. Both can dramatically reduce train-induced wind surge and train noise on the platform. They are also very good in terms of energy optimisation for heating, ventilation and air conditioning (HVAC). All of these effects are stronger with Hermetic PSDs which have an air seal at the top that is mostly used to house wiring and other technology fittings, hence often called the *header box* or *technology wall*.

The term ***Automatic Platform Gates (APGs)*** is used mostly when referring to approximately half-height platform doors that have glass panels. The heights of APGs differ from one supplier to another but are generally in the range of 1.3-1.7 metres tall (ST Engineering, 2019; Westinghouse, 2012). APGs do not provide complete safety protection because people can jump over to the trackside as an act of suicide, or tall passengers may put their heads over the doors which could lead to incidents. However, these types of doors are usually cheaper than full-height doors, easier to install, and are more often used at above ground stations where neither wind surge nor air conditioning are important considerations. In some rail systems such as the Seoul Metro, APGs are referred to as *open railing PSDs* (Kim and Ko, 2018) but they are most generally called *half-height PSDs*. Examples of these are given in Appendix C.2.

The term ***Platform Safety Gates (PSGs)*** is used when referring to simpler platform barriers that usually do not have the glass door leaves, having only the barriers to keep people away from the platform edge. The doorways are structurally open and do not have any moving parts. They are mostly used on LRT platforms. Appendix C.1 shows images of some examples of PSGs.

Lastly, and contrary to conventional PSDs, there are *Vertical PSD* (VPSD) configurations that have longer Section panels and open vertically, unlike the horizontal door movements of conventional PSDs. VPSDs have different designs, some made up of glass and metal frames, others with just metal bars or a set of ropes fixed on vertical columns on the platform. Most of these designs operate only in trials (experimental) as the concept is still immature. Examples are shown in Appendix C.4.

In summary, the PSD types are;

1. Hermetic PSDs
2. Semi-hermetic PEDs
3. Half-height APGs
4. Platform safety gates
5. Vertical PSDs

4.4 Prioritisation of Benefits for Installing PSDs

PSDs are deployed to serve a number of functions. Priorities are given to certain functions depending on the rail system and geographic location, sometimes governed by climate condition and often to reduce or eradicate suicides.

PSD functions according to suppliers such as NRT (2019c), ST Engineering (2019), Gilgen (2016), Faiveley (2010), and Westinghouse (2012), etc., as mentioned on their respective web pages and marketing leaflets, include:

1. Passenger safety - prevention of platform incidents such as accidental fall, suicide, trespass and crime.
2. Noise reduction on the platform
3. Comfort on the platform - reduction of wind and dust
4. Energy efficiency - reduction of HVAC consumption

However, as identified through a survey, not all clients (rail industries) install PSDs for the generally perceived benefit of safety. These include the Hong Kong MTR and the London Underground (LUL). The main priorities discovered from the industry point of view are:

1. Energy efficiency for HVAC (Hong Kong MTR, Singapore MRT)
2. Enhanced station environment (Hong Kong MTR)
3. Prevention of excessive wind speed [piston effect] (LUL)
4. Passenger safety (Singapore MRT)

These are the primary functions that usually govern the decision to install the doors. The rest of the functions often come as value-adding factors but are not primarily the decision drivers. But there are more factors, as identified by researchers and summarised by Abdurrahman *et al.* (2018) in Section 4.9.

In addition, there are secondary functions of PSDs, termed in this thesis as optional PSD functions. They are mainly dependent on customer preference (NRT, 2019a) and therefore not common to most PSD designs but can add value to the PSDs. They include closing the PTI gap, incorporating light-emitting diode (LED) light, environment conditioning (heating/cooling) and media functions. These are all discussed in Section 5.5.13.

4.5 Structure and Components of PSDs

PSDs are usually produced in modules which are assembled to form the subsystem. The components are often assembled and tested off-site to make sure they have the right dimensions and that the interfaces work well before delivering to site to be assembled as a subsystem through what is termed *modular installation*. The PSD subsystem will then be integrated into the train control system.

For the control of PSDs, a room (which may or may not be a dedicated room) called the *Door Control Room* (DCR) is needed for installation of the station control system including a central computer, maintenance system and a monitoring system. In addition, other integration elements may be required, such as an integration control board, radio frequency (RF) integration devices, etc. Figure 4.1 shows an example from Seoul of the various components that work together for successful operation of PSDs. The DCR will include all of these components/functions.

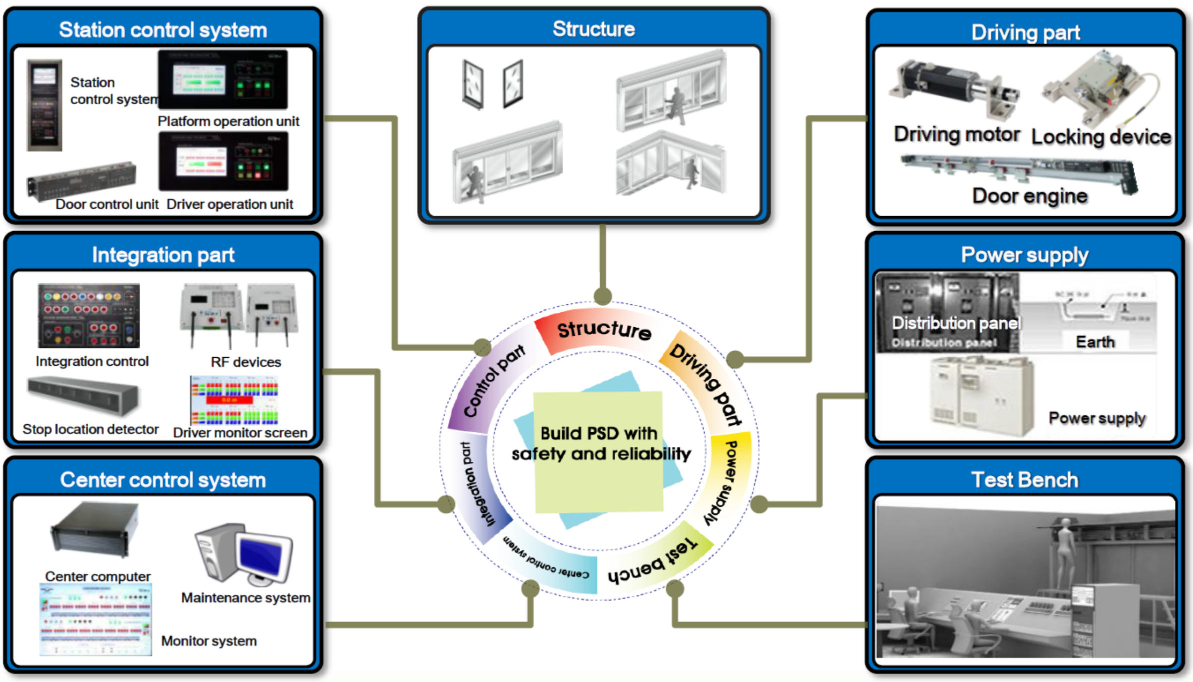


FIGURE 4.1: PSD System Structure [SMRT Seoul Case (Chung, 2013)]

Some PSD systems do not have a dedicated DCR to house this equipment but are integrated into the *Operations (ops) Control Centre* (OCC), where a staff member of the ops control team can be assigned to look over the PSD system. This is the case for the Jubilee Line in London.

The main components of the door structure (middle top Section of Figure 4.1) are (Knorr-Bremse, 2018):

1. Fixed panels (FPs)
2. Automatic sliding doors (ASDs) [both right- and left-hand leaves]
3. Emergency egress doors (EEDs)
4. Driver's doors (DDs)
5. Local Control Panel (LCP)

These components differ for different PSD designs. Some systems (e.g., Crossrail) have EEDs on every door unit or in alternate positions, whereas some have them only at the ends of the platform (e.g., Singapore MRT).

ASDs communicate with the signalling and control system to synchronise opening or closing with train doors, and there may be a difference of up to a few seconds in their respective operation (see Section 4.7). ASDs usually have an Emergency Release Mechanism (ERM), manually operated mechanical locks for passenger use in an emergency (examples in Appendix C.6).

An LCP is a panel consisting of a set of control buttons on the platform for use by passengers and platform staff, especially when doors fail or during an emergency. These are not very common in PSD systems and also differ from one design to another. Some of the recent PSD designs feature them on every door unit along the platform, for example on the Stockholm City Line (Citybanan) in Sweden (see Appendix C.7).

4.6 Reliability of PSDs

PSDs, like any other equipment, are prone to occasional failures occurring during operations. That is why maintenance is an important part of PSD deployment and is often included in the main supply contract for PSDs for a certain period of time before transferring the responsibility of maintenance to the infrastructure/station managers who will then incorporate it into their asset management plans in accordance with common practice (BSI, 2014).

Some PSD components have predefined task periods after which they are due for replacement (otherwise known as quantitative performance metrics in the BSI (2014) ISO 55000 standard). This depends on the frequency of service on the line, which directly influences the number of activations per day (Knorr-Bremse, 2018). Nevertheless, premature replacement of some components is often carried out ahead of failure, in accordance with the cyclical maintenance plan for the door system which sets out the types of maintenance tasks and the recommended time at which they should be conducted, e.g., every month, 6-monthly or annual.

Another alternative is to adapt condition-based maintenance, where condition monitoring would be imposed on selected components to predict the most suitable time for maintenance/replacement, thereby enabling an optimised use period and informed asset investment decision (Britton *et al.*, 2017). This, when effective, can reduce PSD maintenance cost thereby reducing the cost aspect of PSD evaluation.

Some of the parts of PSDs that require maintenance are (Deegan *et al.*, 2015; Knorr-Bremse, 2018):

1. Drive belt
2. Door seals
3. Media panel
4. Earthing and bonding (insulators)
5. EED Panic bar
6. Nose rubbers
7. Door guide plates (door track)
8. ERM on door leaves

9. Mode switch
10. Fixings and fastenings
11. ASD sounders
12. Roller and other load bearing parts
13. Door status indicator
14. Ready to depart indicator
15. Door control units
16. Surge protector
17. Power multimeter
18. Local power supply units
19. Cable and wiring
20. Driving motors

There are, however, some problems that occur more often than others. Some of the most common practical problems reported on the Hong Kong MTR include failure to open or close and lock, and false alarm of gap hazard detection. This happens quite frequently, a '*few times per week*' as reported in the survey conducted as part of this research. For PSDs in the UK, common failures are associated with door pins for the door lock mechanism, happening on average fortnightly, and the door rubbers that pose regular adhesion problems.

In Singapore, there have been issues such as misalignment of the PSDs, which in one incident caused contact with the side of an approaching train, resulting in a disruption of morning peak service on the Downtown line. This was caused by a PSDs bolt loosening over time, which led to dislocation of the PSD guiding rail (CNA, 2018a). On another occasion, Singapore's North-South line suffered a rush hour delay due to a PSD failure, leaving the doors wide open (CNA, 2018b).

Because PSDs are at the PTI which all boarding and alighting passengers have to cross, any failure during operation hours requires immediate action. The easiest action is to deploy staff on site and isolate the door set with the problem, enabling postponement of the repair (if possible) until engineering hours (at night) in order to avoid disruption of the train service (Deegan *et al.*, 2015).

Different types of maintenance work require different access types as categorised in Table 4.1. These are sometimes colour-coded *green* to *red* as best practice for efficient accessibility management. Green means access to platform only, while red represents access to and from the trackside.

These reliability issues that may affect passenger safety or the rail service, e.g., disruption, are important issues to be aware of when considering the deployment of PSDs. The issues are identified and embedded into the SD model (Figure 5.2) to provide a clear picture of what might be affected when PSDs are deployed. This includes recognising the maintenance requirements of the PSD system as a subsystem belonging to the larger system of systems (the railway).

TABLE 4.1: Types of Access Required for PSD Maintenance (Knorr-Bremse, 2018)

Colour Code	Access	Description
(green)	Platform	Access required from the platform side only with doors closed.
(yellow)	Open	Access from the platform only but activities require the doors to be slightly open, breaking the *closed & locked* signal.
(orange)	Protected	Activities require the doors to be fully open, and tools or maintainers may breach the kinematic envelope of the rolling stock.
(pink)	Check	Access to platform door control cabinet required. The cabinet may be located on the trackside or in the DCR.
(red)	Track	Access required from the trackside.

4.7 PSDs and the Signalling Control System

A signalling control system (SCS) is used in railways to safely control the movement of trains by allocating right of access to certain sections of the railway tracks to a particular train at a particular point in time, thereby keeping trains at a safe distance from each other to avoid collision. The train movement (acceleration, deceleration, and braking) is regulated by the SCS (NRC, 2019).

The usual configuration with automated PSDs, is that the SCS will only allow trains to enter a platform when the platform doors are closed, for the purposes of safety. If any of the platform doors are open, the SCS does not allow trains to enter the platform. This usually applies to systems having Automatic Train Protection (ATP) vis-à-vis *Grades of Automation* (GoA) 1 to 4 (see Figure 4.2).

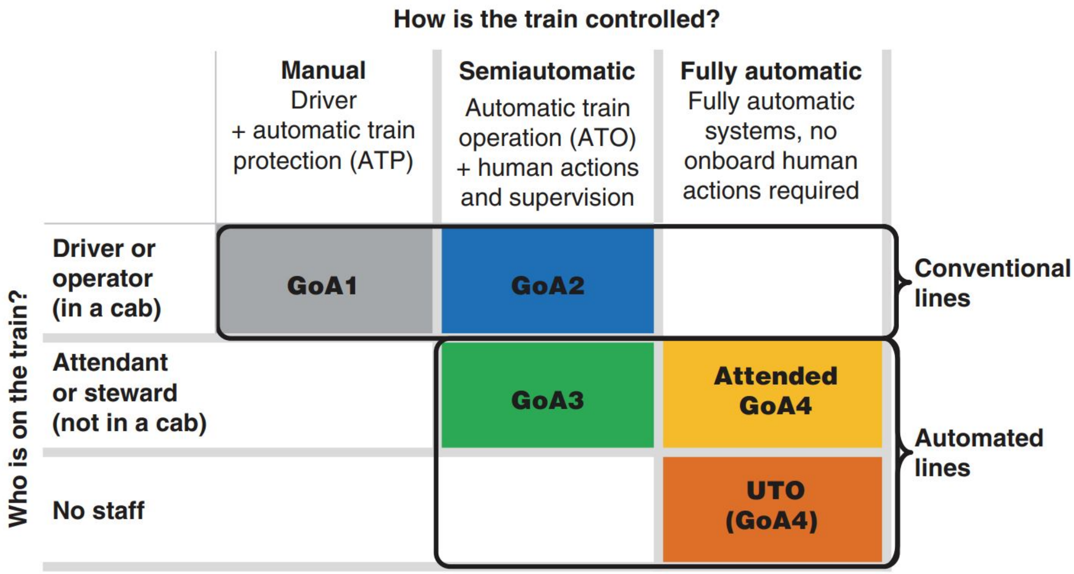


FIGURE 4.2: Grades of Automation [Adapted from Cohen *et al.* (2015)]

Upon entry of the train into the platform, the berthing (which may be linked to the SCS or manually operated by the driver depending on the GoA) aligns the PSDs and the train doors within a position tolerance. Then (in the case of GoA3 and GoA4), the SCS issues a command to the PSDs and the train to open their doors, allowing bidirectional passenger flow between the train and the platform.

When the dwelling is completed or the timetabled departure time has arrived, the SCS issues another command for both sets of doors to close (GoA3 and GoA4), and then waits for the closed and locked feedback signal from the PSDs (Knorr-Bremse, 2018). This ensures that the train does not receive a departure signal until both the platform doors and the train doors are in the closed position. In the case of a GoA below 3, the door opening and closing is controlled from the cab by the driver.

In the event of any of the doorways on the PSD being 'locked out of service', the PSD (depending on the GoA) communicates such information to the SCS and further to the arriving train to prevent the corresponding doors opening during the station stop. This should also apply when the train doors are 'locked out of use'.

4.8 Metro versus Mainline Systems

PSDs are most common on metro systems across the globe and are quite rare on mainline networks. This can be associated to two distinctive features, namely station position (above ground or underground) and train configuration.

4.8.1 Above Ground Versus Underground

The decision of whether to place a station above ground or underground is reliant upon factors such as urban design, route planning, construction, engineering, economics and politics (ITA, 2004). However, stations on mainline systems, otherwise known as conventional rail, intercity or regional rail systems, are usually placed above ground (surface or elevated). Therefore, in most cases, platforms require no artificial ventilation due to their exposure to the ambient temperature. Hence, PSDs may not be used for ventilation or energy purposes, but for other objectives such as safety. However, in very hot regions such as the Middle East, PSDs can play the role of enclosing the environment for efficient air conditioning. An example of this is the Dubai metro which has full-height PSDs even in above ground stations (see Appendix C.3).

It is common practice for above ground stations featuring PSDs to have half-height doors, rather than full-height ones because even with full-height doors, the platforms would still be exposed to the ambient temperatures. An example of this is the above ground stations in Singapore, featuring half-height doors but also having ventilation fans on the platforms as shown in Appendix C.2. This is to enhance passenger comfort due to the high temperature and humidity in the country.

4.8.2 Train Configuration

Most metro systems run the same type of rolling stock through specific rail lines - one rolling stock type per line, e.g., Singapore MRT. In that case, having PSDs does not affect the operation in terms of its restrictive nature for door positions. There are cases, however, where rolling stock of varying configurations (door geometry, kinematic envelope, etc.) is cascaded together to run as a single service; the same rolling stock is used for multiple lines (inter-working); or different rolling stock runs on different lines but shares the same platform, e.g., London Underground (Polhill, 2016). In these situations, there is limited potential for fitting PSDs because of compatibility problems with the varying rolling stock configurations.

The diverse nature of operations and varying fleet configurations are most common on mainline networks which further constrains having PSDs on their platforms. This can be a factor that would discourage consideration of having conventional PSDs on mainline platforms. However, VPSDs can solve this problem and enable normal operation with varying train door positions and also allow a wider train (stopping) position tolerance (examples in Appendix C.4).

4.9 Benefits Associated with PSDs

The identified benefits of having PSDs are listed in Table 4.2, many of which were acknowledged and referenced in a paper produced by the author as part of this research (Abdurrahman *et al.*, 2018). The process that was followed to compile the list is explained in Section 3.3.

Not all of these benefits are obvious to most rail operators. Even if they are, decisions to install doors are usually only based on a few of the major benefits. This was discovered from the inquiries sent to some of the major rail operators in the world regarding their reasons for installing PSDs. The responses received (as in Section 4.4) only itemise things like the optimisation of HVAC energy consumption, safety, enhanced station environment, and for ventilation purposes (addressing the piston effect) on platforms.

TABLE 4.2: Benefits of PSDs

S/N	Benefits	Comments
1	Noise mitigation	Analysed and quantified in Section 5.3.
2	Air quality improvement	
3	Dust suppression	
4	Reduced lost customer hours	
5	Increased platform space	
6	Lower platform cleaning costs	
7	Fewer platform staff	
8	Optimisation of HVAC energy consumption	
9	Safety – Prevention of accidental falls	
10	Safety – Prevention of trespass	
11	Safety – Suicide prevention	
12	Passenger flow improvement (effect on dwell time)	
13	Less service disruption	
14	Less workforce trauma	
15	Prevention of sudden smoke spread in case of subway fire	Discussed in Section 5.5, summarised and estimated in Appendix D.
16	Prevention of trash on the line (track safety)	
17	Provision of level access	
18	Prevention of platform against flooding	
19	Sense of security for waiting passengers	
20	Sound quality improvement for platform announcements	
21	Wind surge suppression	
22	Enhanced station environment	
23	Aesthetics/Attractiveness	
24	Less passenger trauma	
25	Passenger crowd control	

4.10 Disbenefits Associated with PSDs

The costs and disbenefits associated with PSD deployment are listed in Table 4.3. This is also in line with the paper produced as part of this research (Abdurrahman *et al.*, 2018).

Some of the disbenefits have a significant impact on the operations of the railway, for example any dwell time extension has a direct impact on capacity even if the extension is only by a few seconds. This particular factor varies from one system to another: it could be zero in some systems or may even reduce the dwell time if its dynamic component is reduced. This is elaborated further and mathematically modelled in Section 5.3.10.

TABLE 4.3: Costs and Disbenefits of PSDs

S/N	Costs/Disbenefits	Comments
1	Additional staffing for door control	Analysed and quantified in Section 5.3.
2	Cost of integration, testing (using trial trains) and commissioning	
3	Cost of purchase	
4	Dwell time extension (impact on capacity)	
5	Redundant train energy consumption	
6	Function energy requirement	
7	Power supply devices required	
8	Impact of service disruption on revenue	
9	Investment for DCR and its contents	
10	Cost of half-life overhaul	
11	Maintenance requirements	
12	Possibility of mantrap	
13	Limiting the rolling stock types	Discussed in Section 5.5, summarised and estimated in Appendix D.
14	Extension of emergency evacuation period	
15	Reliability issues	
16	Service disruption during installation (retrofit)	
17	DCR staff training	

The costs/disbenefits listed in Table 4.3 are divided into those quantified in detail and those that are only estimated. To further provide clarity, the pure costs are separated from the disbenefits as shown in Table 4.4.

4.11 Business Case for PSDs

A business case, according to TfL (2013a), refers to a piece of work (mostly written) that sets out a clear justification and therefore recommends further action for carrying

TABLE 4.4: Pure Costs Versus Disbenefits of PSDs

Pure Cost	Disbenefits
Staffing	Dwell time, capacity losses
Integration, testing & and commissioning	Service disruption and effect on revenue
Cost of purchase (including devices)	Mantrap risk
Energy	Limitation on train types
DCR investment (where required)	Impact on emergency evacuation
Maintenance (including overhaul)	Disruption during retrofit
(Un)reliability	Track impact for ATO
Staff training	

out a project or a particular option in the project.

As far as the author's research could establish, there is no evidence to suggest that the surveyed rail systems have any standard or legal regulation covering the necessity or otherwise of installing PSDs. In which case, the decision to install them depends on the judgement of the relevant officials running the systems at the time they are designed. However, if the installation has a safety motivation as a result of frequent occurrence of incidents leading to deaths and injuries, then it would be the case that measures (not necessarily PSDs) have to be introduced to mitigate the risks to 'as low as is reasonably practicable' (ALARP). But if it is decided that PSDs would be retrofitted on existing platforms, then it could be a significant change that attracts the necessity to comply with the CSM-RA regulation as discussed in Section 2.6.1.

One of the metro operators contacted reported that there was no business case for PSDs[1]. It was anticipated that the benefits of having them would not pay for their installation but they were installed anyway. The estimation technique used was not clear but it was understood that there were only three anticipated benefits, namely safety, air conditioning saving and a better station environment.

In response from another rail system, a Chief Operations Officer said:

[1]Organisations contacted include Crossrail, SMRT, MTR, LUL and TfL

'In terms of the original decision to fit doors... I don't think that was an economic one; the widespread perception amongst designers (I believe) is that if you can fit platform doors – generally at underground stations so top and bottom fixings, and used by one type of stock – then it's hard to justify not doing so from a safety perspective. ...I don't think company_name[2] has a rich history of optioneering and analysis of doors.'

This came in as part of statements indicating that there was no consistent approach to evaluation, but the doors were installed anyway despite the need to develop a proper business case, as is the case for other projects in most organisations, e.g., DfT (2018b), Metrolinx (2019), TfL (2013b), DfT (2013), etc. However, this is not surprising considering the fact that the railways is seen as not so fast in adoption of conventional cost benefit analysis for appraisal of safety-related measures (Evans, 2013).

In contrast with the previous cases, however, another system operator revealed that a business case was developed for a line in one of the prominent cities, but due to funding issues, the PSDs were not installed despite the estimated (mostly safety) benefits making a good case for installing the doors in accordance with the company's Benefit-Cost Ratio (BCR) requirements.

In summary, what has been discovered from the surveys made as part of this research is that there is no standard regulation, business case procedure or evaluation process regarding the decision whether to deploy platform doors. This thesis therefore aims to highlight issues associated with PSDs and provide a tool that can be useful for those considering deploying the doors.

4.12 Summary

A background on platform barriers is given in this Chapter as a foundation to understanding them. A significant part of the thesis is presented in the next Chapter, in

[2]Concealed for confidentiality.

which the models are developed and the PSD factors are quantified using mathematical equations that are developed for the purpose.

Chapter 5

Quantification of PSD Factors

5.1 Preamble

In this Chapter, the methodology described in Chapter 3 is put into practice to provide a solution to the problem stated in Section 1.3.

The Chapter presents the SD model developed for the PSDs and discusses issues around it. The SD model (formed as a CLD) is a graphical display for all factors identified as being affected by the presence of PSDs, giving an overview of the issues at hand. Also discussed in this Chapter is the development of mathematical models, stating precisely the relationships existing among the modelled variables. Figure 5.1 summarises the modelling process followed.

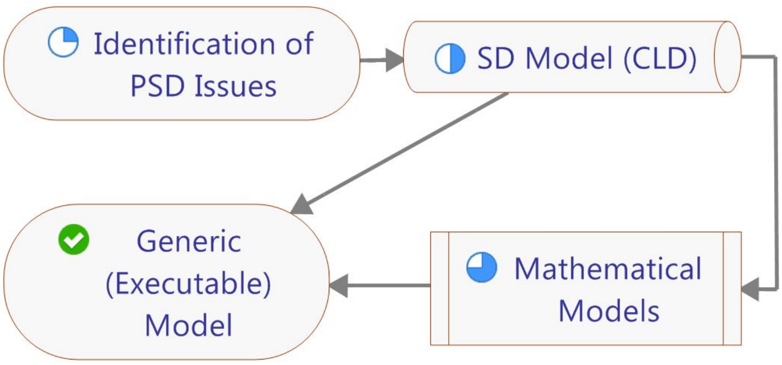


FIGURE 5.1: Modelling Process (Author)

The generic model is executable and has a dedicated page for data input, enabling customisation for a particular platform, station, railway line or an entire rail network. Details of how to use the model are presented in Section 6.3.1 and can also be extracted and used as a guide by potential users of the model.

5.2 System Dynamics Model

In order to establish a clear understanding of the causes and effects around the various railway issues affected by the installation of platform doors, an SD model (Figure 5.2) was created in the form of a CLD, to enable depiction of the linear and nonlinear behaviours of these causes and effects which can be considered as a complex system in accordance with the definition of complex systems given by Sayama (2015) who describes it as a network composed of several components that interact with each other in a typically nonlinear fashion. Without the SD model, it would have been highly intractable to understand the complex nature of the effects of deploying PSDs on platforms, let alone attempting to quantify those effects.

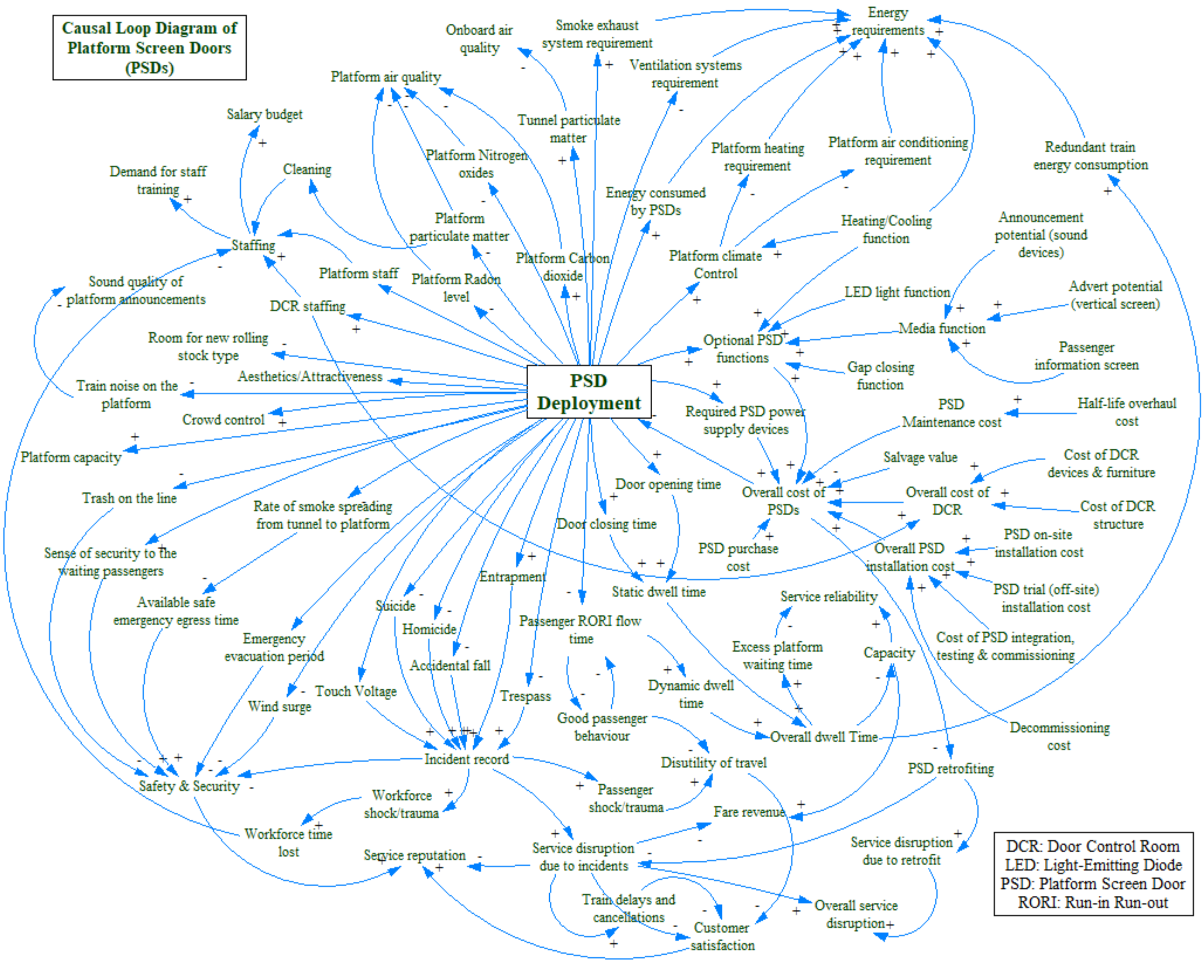


FIGURE 5.2: SD Model for PSDs [in the form of a CLD] (Author)

The CLD has been proven to do well in recent *cause and effect* scenarios (Abdurrahman *et al.*, 2018; Zolfaghari and Blumenfeld, 2016). It has therefore been developed to present all identified interactions between PSDs and various components of the railway system. This provides a guideline for parties considering the installation of PSDs, so that they can be aware of what might be affected by their decision.

Factors from the SD model were further modelled mathematically to enable an estimation of the magnitude of effects that could be incurred (see Figure 5.3).

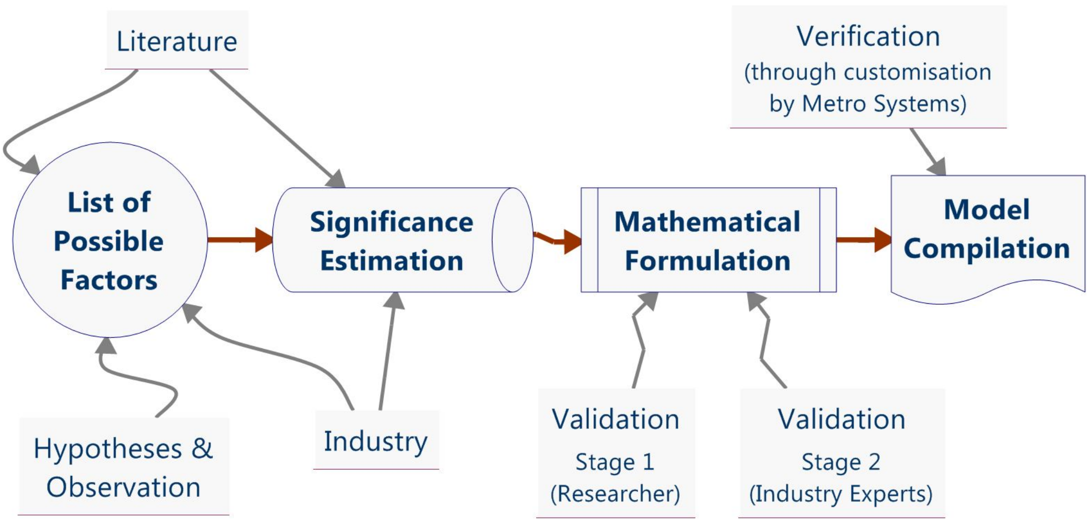


FIGURE 5.3: Identification and Validation Process (Author)

Each factor may be measured in different terms, but to enable the comparison and ranking of the importance of each, the author has sought to convert each measure into a common (currency) unit. Money would, in any case, be one of the key determining factors for making the decision to deploy PSDs.

Mathematical models have been created for the identified significant issues indicated on the SD model, to enable the development of advice for decision makers (see Section 5.3). The SD model serves as a framework for reference and assessment of the various issues on rail systems that are affected by PSDs.

5.2.1 Polarity in the CLD

The SD model (Figure 5.2) is formed of positive (+) and negative (-) polarities. For example, it was indicated that the presence of PSDs may reduce the possibility of *suicide, homicide, accidental fall* and *trespass*. These all have a negative polarity because they will decrease if PSDs are deployed. However, *entrapment* has a positive polarity, indicating that with PSDs, the possibility of passenger entrapment between doors would increase.

Moving along the Figure, the positive polarities pointing towards the incident record show that increases in the preceding factors (*suicide, homicide, accidental fall, trespass, entrapment*) would all yield a corresponding increase in the *incident record* for that particular platform, all other things being equal.

Another example is the case of platform *particulate matter* (PM) known as the *PM concentrations*. The presence of PSDs yields a decrease in the quantity of platform PM as indicated by the negative polarity in the model (Figure 5.2). This is because PSDs serve as a shield to the PM coming from the trackside onto platforms due to train movements.

Moving further along the trend, the *platform air quality* would decrease (having negative polarity) with an increase in the *platform PM*. But *cleaning* requirements for the platform has a positive polarity because it would certainly increase if the *platform PM* increases, ceteris paribus.

The polarity concept is therefore crucial to understanding the relationships among the various issues present in the SD model.

5.2.2 Causes Tree

As part of the validation process for the issues mapped around the deployment of PSDs, *causes tree* diagrams were produced for the factors in the SD model. These improve understanding of the relationships by displaying an abstract representation of the factors causing changes in the particular issue being considered.

Causes tree diagrams provide a chain of causes (in a tree form) leading to a change in a particular element of interest in a complex system. Their graphical form makes the causal structure easy to comprehend. As an example, Figure 5.4 shows the *causes tree* for factors affecting the *overall dwell time*.

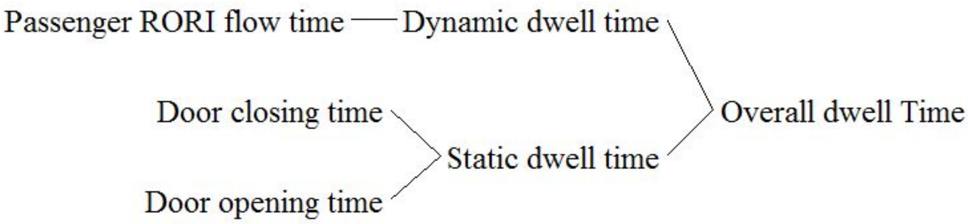


FIGURE 5.4: Causes Tree Diagram for Overall Dwell Time (Author)

From the Figure, it can be seen that there are two factors capable of directly causing changes to the *overall dwell time*, namely the *dynamic dwell time* and the *static dwell time*. These are the two components of dwell time, 'dynamic' being the time component during which the actual passenger movements across the PTI occur, and 'static' being the time it takes for the doors to open and close. The higher stage of detail shows the factors responsible for causing the change from the base point of view, namely; the *passenger run-out/run-in (RORI) time* for the dynamic component, and the *door opening and closing times* for the static component.

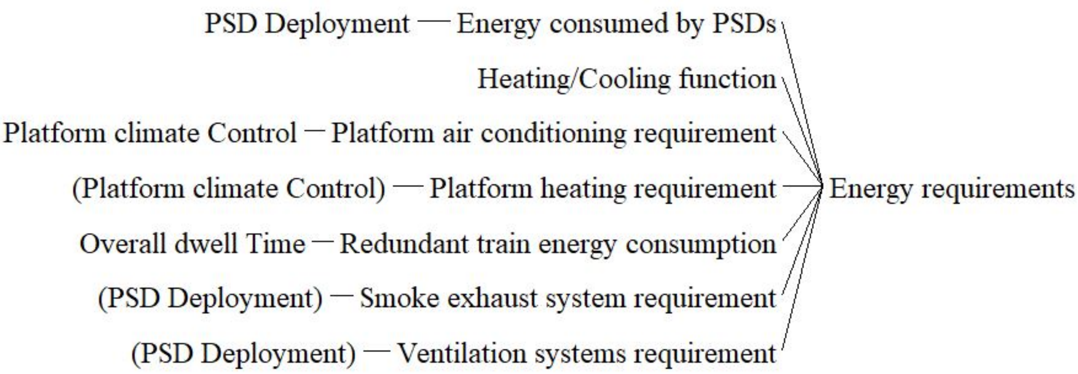


FIGURE 5.5: Causes Tree Diagram for Energy Requirements (Author)

Another self-explanatory example of a *causes tree* is the one for *energy requirements* shown in Figure 5.5. The Figure indicates the ways in which the deployment of PSDs could induce a change in the total energy consumption requirements associated with a particular station. These include the energy required by the PSDs to function, the optional heating/cooling feature of some PSDs, the change in platform air conditioning and/or heating requirements due to having a barrier isolating the platform from the track area, the extra (smaller) hotel load of the trains dwelling on the platform due to a change in dwell time, and the change in smoke exhaust and ventilation requirements due to space partitioning posed by the PSDs.

5.2.3 Uses Tree

Another key function of an SD model is the *uses tree* which is more or less the opposite of the *causes tree* described in Section 5.2.2. A *uses tree* is a tool showing the forward effects of a root cause, to ease the understanding of how various elements of a complex system are affected by preceding elements. Zolfaghari *et al.* (2016), for example, used a *uses tree* to explain how subsystems are affected by a complex metro system environment; this made the argument easier to understand. *Uses tree* contributes to this research through verification of the causal relationships among various issues of the SD model.

A *uses tree* is also usually represented by a diagram that shows, for a particular element, the use scenarios causing a change in subsequent other elements. As an example from the PSD CLD, the *uses tree* for an incident record is presented in Figure 5.6, depicting the various components that could be affected following a change in the *incident record* of a particular platform. It can be seen from the Figure that there is another subcategory of *uses tree* radiating from the *service disruption due to incidents*, leading to many other factors being affected. The *overall service disruption* is there because there are other factors affecting service disruption, not only those due to incidents. These include technical failures along the line, weather conditions which may lead to cancellation of service, planned and/or unplanned disruptions, etc.

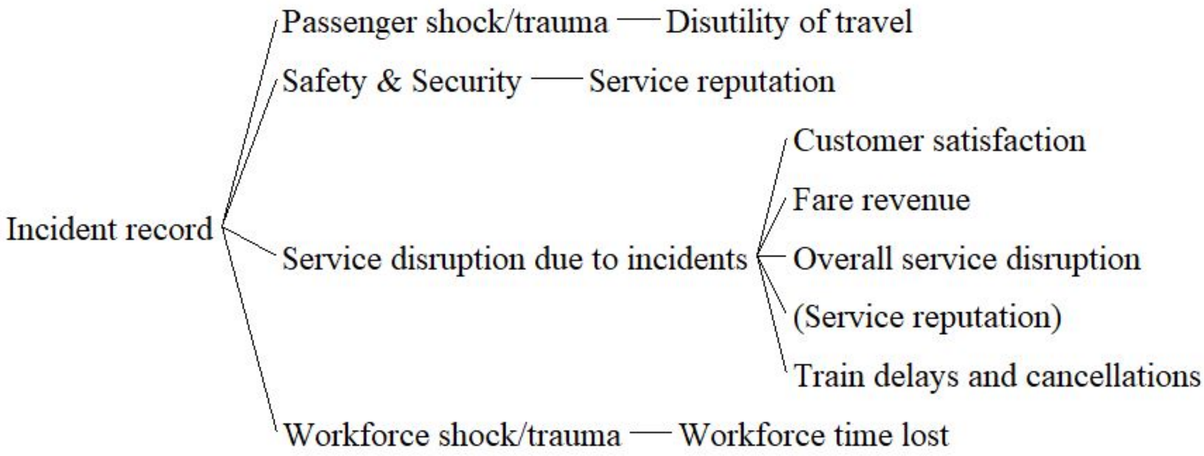


FIGURE 5.6: Uses Tree Diagram for Incident Record (Author)

5.3 Mathematical Models

The identified issues associated with PSD deployment (Figure 5.2) were mathematically modelled in an effort to estimate the impact of each on the overall rail network. The equations generated were further used in the development of the generic spreadsheet model that provides a checklist and support for decision makers in deciding whether or not to deploy PSDs.

A total of 85 factors in the railway system were identified as being affected as a result of PSD deployment. A significant number of these (61, forming about 72% of the total as shown in Figure 5.7) were identified for incorporation into the executable model using mathematical equations developed as part of this research which are presented in the respective sections from 5.3.1 onward.

Twenty-four factors (about 28%) were not mathematically quantified, for the reasons stated in sections 5.4 and 5.5. These relate to such reasons as the factor being likely to be quantitatively immaterial, have the potential to yield both positive and negative effects within small magnitudes and therefore considered neutral, or require no mathematical modelling as it either contributes to a larger aspect of the railway and therefore a fraction of it, e.g., *customer satisfaction*, or that it is merely a process that needs to be acknowledged but is not in itself of particular benefit or disbenefit, e.g., *PSD retrofitting*, etc. For the purpose of reference and for the default model, the author has defined

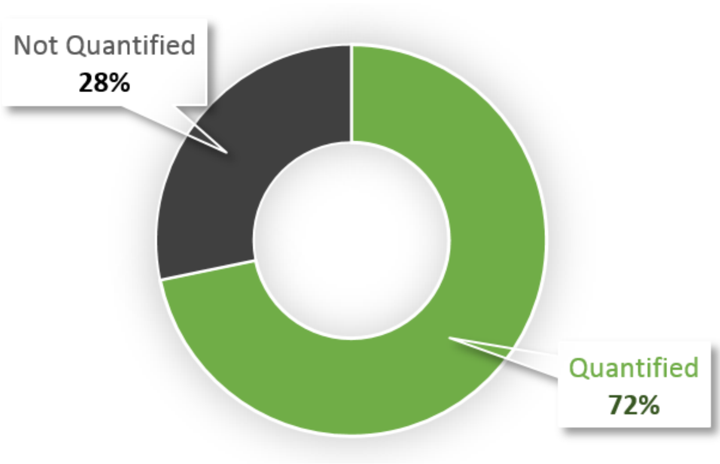


FIGURE 5.7: Numeric Distribution of the Quantified PSD Factors (Author)

these factors as *'immaterial'*. These factors are indicated and colour-coded in *black* type in Figure 5.8. Factors shown in *Green* in the Figure are those that are quantified and incorporated in the executable model.

However, the unquantified factors were nevertheless evaluated, to estimate their significance or otherwise. A crude estimate of each of these factors is given in Appendix D. The estimated benefits (positives in the appendix) and disbenefits (negatives) were compared against the quantified benefits and disbenefits, and it was evident from the comparison (see Figure 5.9) based on the crude estimates used that they are immaterial to the overall evaluation.

5.3.1 Safety Issues

The factors considered under *safety* which could occur at the PTI are *accidental fall*, *suicide*, *trespass*, *entrapment* and *workforce shock/trauma*, the majority of which were informed by the RSSB's consideration for railway safety performance (see RSSB, 2017a). These were modelled as shown in the respective equations that follow.

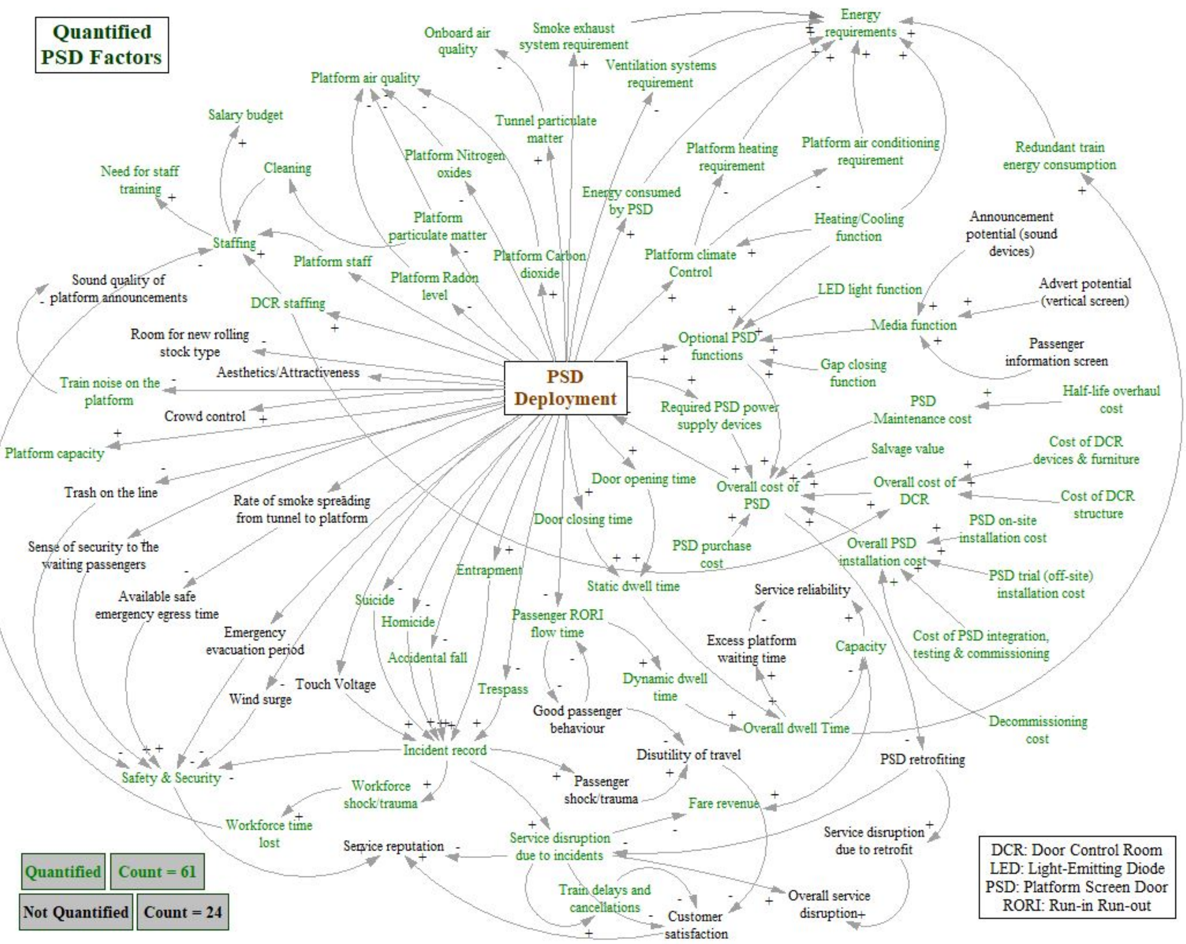


FIGURE 5.8: Quantified PSD Factors Mapped onto the CLD (Author)

Incident Record

The total incident record is the algebraic sum of the individual incidents as indicated by equation 5.1, with a common unit of *fatalities and weighted injuries (FWI)/year*[1]. These can be obtained directly from the record of platform occurrences at each station.

$$I_r = \sum_{t=1}^{n} i_t \tag{5.1}$$

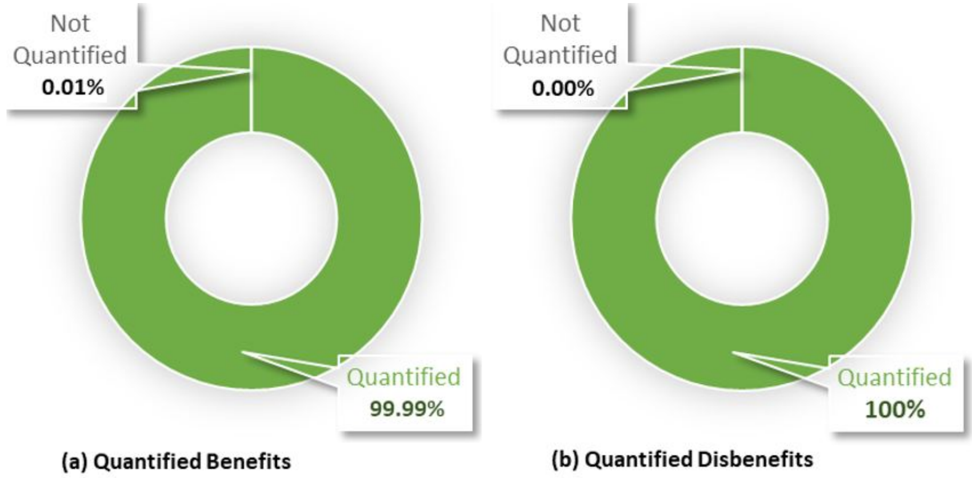
Where:

I_r = total incident record (FWI/yr)

i_t = individual incident record for t type of incidents (FWI/yr)

n = number of incident types recorded

[1]FWI is used in railways to measure the consequences of accidents combining both fatalities and injuries (Evans, 2017).



	Benefits	Disbenefits
Value of Quantified (£)	11,484,688	11,756,148
Estimate of Unquantified (£)	1,354	173

FIGURE 5.9: Comparison of Quantified and Unquantified PSD Factors [Details in Appendix D] (Author)

or, more clearly:

$$incidentrecord = accidentalfall + suicide + trespass + entrapment \tag{5.2}$$

Workforce Shock/Trauma

Incidents of workforce shock/trauma may also be obtained from the *incident record*. For situations where there is no exact record of these at a station of interest, a relationship has been developed to estimate the workforce shock/trauma that may be experienced because of incidents. The relationship was developed using the 10-year British mainline network data obtained from the RSSB's annual safety performance report (ASPR 2016/17) (RSSB, 2017a), which is assumed to be reasonably applicable not only for a mainline network but for a metro as well, since there is unlikely to be any significant difference between the magnitude of a driver's shock/trauma that would be experienced as a result of being involved in a similar incident irrespective of where it occurs – mainline or metro, as a fatality is always a fatality, wherever it happens.

The reported 10-year average number of suicide incidents from 2007/08 to 2016/17 inclusive was *246.02 FWI/yr* which yielded a 10-year average workforce shock/trauma of

1.09 FWI/yr. The ratio of these is termed the rate of workforce shock/trauma (equation 5.3).

$$\begin{aligned} R_{\tau} &= \frac{Avg.\ workforce\ harm\ (FWI/yr)}{Avg.\ suicide\ incidents\ (FWI/yr)} \\ &= \frac{1.09}{246.02} = 0.00443 \end{aligned} \tag{5.3}$$

Where:

> R_{τ} = rate of workforce shock/trauma, the rate of harm that could be caused as a result of an incident leading to *1 FWI*.

Equation 5.3 was based on real-world data, and it yielded *0.00443* as the rate of workforce harm, which is very close to the theoretical value *(0.005)* for Class I trauma (RSSB, 2017a) which could be used in this case since, by definition, Class I trauma is that which is caused by witnessing a fatal incident.

Therefore, the workforce shock/trauma (τ) in *FWI/yr* can be obtained from equation 5.4, thus:

$$\begin{aligned} \tau &= R_{\tau} \times I_r \\ &= 0.005(I_r) \end{aligned} \tag{5.4}$$

The total safety record, S_r, in *FWI/yr* would be:

$$\begin{aligned} S_r &= I_r + \tau \\ &= 1.005(I_r) \end{aligned} \tag{5.5}$$

Value of Total Safety Issues

To assign monetary values to the total safety issues, the *value of preventing a fatality* (VPF) is needed. VPF is the term used by the RSSB to refer to the monetary Figure that is believed to be equivalent in value to one human life. It is used in decision-making processes for the valuation of safety-related benefits and disbenefits (RSSB, 2018b). The VPF (£1,946,000) published by RSSB in June 2018, can be used in this case. As such, the value of the total safety record, V_{sr}, in £/yr becomes:

$$\begin{aligned} V_{sr} &= S_r \times VPF \\ &= 1.005(I_r \times VPF) \end{aligned} \tag{5.6}$$

which can also be obtained directly using either equation 5.7 or equation 5.8:

$$V_{sr} = VPF\left(\sum_{t=1}^{n} i_t + \tau\right) \tag{5.7}$$

$$V_{sr} = 1.005\left(\sum_{t=1}^{n} i_t \times VPF\right) \tag{5.8}$$

Where:

$VPF =$ value of a prevented fatality (£/FWI).

The whole procedure for the total safety issues can be carried out for the case with PSDs as well as that without PSDs. The difference can therefore be obtained as the change in safety value that could result from installing PSDs.

5.3.2 Energy Consumption

Energy efficiency has always received attention in many industries, including the railways. There are two main energy consumers in the railway sector: *traction energy* and *non-traction energy* consumption. Traction (usually the largest energy portion) relates to the main supply enabling the trains to move, usually through the Overhead Line Equipment (OLE) in the mainline context or the *third rail* in the metro context. The non-traction energy, on the other hand, refers to all other ways in which energy is consumed, including but not limited to station lighting, commercial activities, powering station machinery and devices, HVAC, etc.

Major metro operators around the world usually report that they use a big proportion of their energy for traction. For example, the two major components of electricity consumption on the Hong Kong MTR are traction and air conditioning (MTR, 2005). To be specific, LUL spends about 75% of its (then) 1.2 TWh/yr annual consumption on traction (Payne, 2013; Webb *et al.*, 2014).

Traction energy is usually optimised through *regenerative braking*, enabling the rolling stock to generate some energy while braking, which can be stored and used later. For the non-traction energy, there are a number of ways in which energy optimisation is achieved, one of which is the deployment of PSDs, which affects the overall energy consumption in three main ways (Abdurrahman *et al.*, 2018):

1. Station HVAC energy
2. PSD function energy
3. Train energy

HVAC Energy

When a PSD set is installed, the HVAC system's energy consumption in the station will change (Hu and Lee, 2004). This is because prior to PSD installation, the area that needs heating or cooling is larger, with the physical boundary being the joint spaces of both the platform and the tunnel, since there is no physical separation in that situation. But with full-height PSDs in place, the area is more confined, having the platform separated from the tunnel, and so the requirements for HVAC energy consumption change.

It was reported in the case of the Seoul Metropolitan Subway (Chung, 2013) that after retrofitting PSDs, the HVAC power consumption dropped by about 130 tonnes of refrigeration (TR) (equivalent to 457 kW), a drop of about 43% from the previous consumption of 300 TR (1,055 kW).

Similarly, in the case of the Singapore MRT, the deployment of full-height PSDs is reported to have reduced the overall HVAC energy consumption by 50% (Thong and Cheong, 2012). However, the energy saving is not always as high as that in Singapore.

It depends on the various factors contributing to the energy requirements, such as climate which necessitates cooling of platforms or, in other cases, heating; the platform area.

A rather low energy saving was reported in the case of the Hong Kong MTR: a 15% reduction in HVAC was associated with PSD presence (Lin, 2016). A response received from a high-ranking official of the MTR confirmed this, indicating an energy saving of between 10% and 20%.

Looking at the three scenarios described, it can be concluded that PSDs can reduce station energy consumption, but the magnitude of the reduction is variable and depends on the station energy requirements and the climate of the region in question. A comparison of the three savings is shown in Figure 5.10.

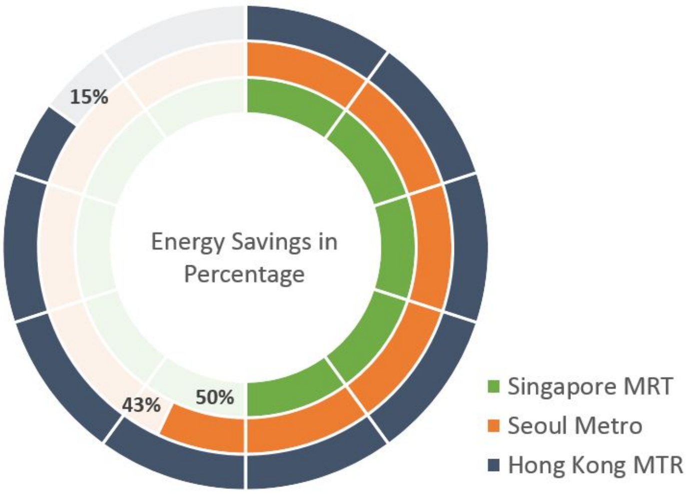


FIGURE 5.10: Energy Savings Associated with PSDs

A noteworthy point here is that the reported energy savings are a result of observations with and without PSDs. The observed energy with PSDs does not take account of the function energy consumed by the PSDs themselves, hence the net change (saving) in HVAC would be lower than the observed energy by an amount equivalent to that consumed by the PSDs. Mathematically:

$$\Delta E_{HVAC} = \left(\Delta E_{observed} \times E_{HVAC}\right) + E_f \qquad (5.9)$$

Where:

ΔE_{HVAC} = change in HVAC energy (kWh/yr)

$\Delta E_{observed}$ = observed energy change in similar systems (in %)

E_{HVAC} = annual HVAC energy consumption (kWh/yr)

E_f = function energy consumed by the PSDs (kWh/yr)

To generally estimate the value of HVAC energy consumption at a given station of interest, the sum of two energy charge components is taken, i.e. the consumption charge and the total standing charge for that station as in equation 5.10.

$$V_{HVAC} = \left(E_{HVAC} \times \mu_e + 365\gamma_{st}\right) \tag{5.10}$$

Where:

V_{HVAC} = the monetary value of HVAC (£/yr)

μ_e = unit cost of energy (£/kWh)

γ_{st} = daily standing charge for station (£/day)

But since the daily standing charge is paid anyway (irrespective of energy consumption), only the value of the change in energy would be subject to the unit cost of energy, thus:

$$V_{\Delta E_{HVAC}} = \left(\Delta E_{HVAC} \times \mu_e\right) \tag{5.11}$$

Where:

$V_{\Delta E_{HVAC}}$ = the monetary value of the change in HVAC (£/yr)

PSD Function Energy

Information about PSD energy consumption is usually provided by the supplier and is therefore known beforehand. For example, a prestigious large railway system that has one of the most recent PSD installations in the world[2] reported that the total maximum

[2] Identity concealed for confidentiality.

power consumption per platform is about 30 kVA including a 25% reserve power factor. This information could be obtained per door unit and used to determine the power consumption of the PSDs in kilowatts (kW), and could further be used to estimate the overall energy consumption for a given period (see equation 5.12).

$$E_f = P_{door} \times n_{pd} \times h_{op} \tag{5.12}$$

Where:

E_f = PSD function energy (kWh/yr)

P_{door} = power consumption per door unit (kW)

n_{pd} = number of door units (per platform)

h_{op} = annual station operation hours (h/yr)

The power consumption provided by the PSD suppliers is usually the peak power rating of the system, including not just the power to move the motors and therefore open/close doors but also for the electrical connection requirements of the door system at peak load.

The number of door units per platform is usually the same as the total number of doorways per train, and can be obtained as a product of the number of cars per train and number of doors per car, thus:

$$n_{pd} = n_{td} = n_{tc} \times n_{cd} \tag{5.13}$$

Where:

n_{td} = number of train doors

n_{tc} = number of cars per train

n_{cd} = number of doors per car

The financial value of the energy used can be obtained from the product of the unit cost of energy and the amount of (function) energy consumed, thus:

$$V_{E_f} = E_f \times \mu_e \tag{5.14}$$

Where:

V_{E_f} = value of PSD function energy (£/yr)

Train Energy

With the observation that PSDs have an effect on the dwell time (Barron *et al.*, 2018), by extension the amount of time trains spend stationary is affected as well. If a few seconds are added to the time a train stays on the platform, it can also add to the train's energy consumption.

Upon consulting experts with experience in rail systems and who currently work on the Crossrail project in the UK, it was found that trains consume only what is termed a *hotel load* while dwelling. The hotel load refers to the energy load required to keep several functions of the train active while it is not in motion. These include lighting, air conditioning or heating. The energy consumed in stations is smaller than that consumed by the train while in motion. However, this is estimated in relation to the impact of PSDs on the increase in dwell time.

It may be a few seconds for one dwell activity, but considering that there are several dwell activities at several platforms over several hours and days, this could become a reasonable sum that requires quantification. An estimate of how much extra energy is consumed by a train delayed by a few seconds can be made using equation 5.15.

$$\Delta_{te} = \frac{E_{st} \times \Delta d \times \lambda \times h_{op}}{3,600} \tag{5.15}$$

Where:

Δ_{te} = change in train energy consumption (kWh/yr)

E_{st} = static train power (kW)

Δd = change in dwell time (s); (+ve for delays, -ve for improved dwelling)

λ = frequency of train on the platform (tph)

In some instances, the information about train power might be unavailable, in which case the product of the cruise velocity (km/h) and train energy consumption per unit distance (kWh/km) at that velocity can be taken to represent the train power.

The change in train energy consumption could be either positive or negative depending on whether the dwell time is reduced or increased. Equation 5.16 can be used to calculate the financial value of this change in energy.

$$V_{\Delta_{te}} = \left(\Delta_{te} \times \mu_e\right) \tag{5.16}$$

Where:

$V_{\Delta_{te}}$ = value of change in train energy consumption (£/yr)

Overall Energy Costs

The overall effect on energy is the sum of the three energy components, namely HVAC energy, PSD function energy and train energy, thus:

$$V_E = V_{\Delta E_{HVAC}} + V_{E_f} + V_{\Delta_{te}} \tag{5.17}$$

Where:

V_E = value of overall energy (£/yr)

5.3.3 Staffing

The deployment of PSDs could affect staffing requirements in four different ways:

1. DCR staff
2. Lost Workforce Hours
3. Cleaning staff
4. Platform staff

DCR Staff

DCR staff are required to monitor the activities of the PSDs network-wide. In systems like the Hong Kong MTR, there are staff on duty specifically for the operation and control of the PSDs. However, in other systems such as the Jubilee Line Extension (JLE) in London, dedicated staff are not required. Instead, a member of staff from the OCC has an additional set of screens with which to monitor the operation and control of the PSDs. The author developed a model which can be used in either case to estimate the impact on staffing of PSD control, as shown in equation 5.18.

$$V_{st_{DCR}} = \left(n_{dc_s} \times S_{dc_s}\right) + C_{tr_s} \tag{5.18}$$

Where:

$V_{st_{DCR}}$ = cost of DCR staff (£/yr)

n_{dc_s} = number of DCR staff required

S_{dc_s} = annual salary of DCR staff (£/yr)

C_{tr_s} = staff training cost incurred in that particular year (£/yr)

Staff training may be conducted by the supplier at no additional cost, if it is part of the PSD contract. If not, then money has to be allocated to training at least the first set of staff, followed by internal training of subsequent staff at no or negligible cost. If needed, a report by EMG (2018) can be used to estimate the training cost which may fall under the information technology (IT) category. It takes an average of 3.2 days, costing nearly £1,600 per number of staff, including instructor and material costs (EMG, 2018).

Lost Workforce Hours

Whenever an incident occurs, there is an inclination for the driver involved to be relieved from their duty for days or weeks depending on the severity of their trauma. The driver's absence from work can be considered as a 'loss' in terms of workforce hours. A replacement driver would have to be made available to carry out the duty of the relieved driver. That replacement driver must be paid for the time they work, as an overtime payment, since it is not part of their work schedule.

In that regard, RSSB (2017a) reported that around 50% of train drivers involved in fatal accidents resume work within 4 weeks of the incident, while around 75% return within 8 weeks. The distribution of these is as displayed in Figure 5.11. The information was derived from suicide cases. Hence, for the sake of analysis, it was assumed that this is for accidents involving a single fatality and not a multi-fatality accident, leading to an assumption of 1 FWI per incident. Adapting this concept yielded an average *workforce time lost* (WTL) of 6 weeks/FWI.

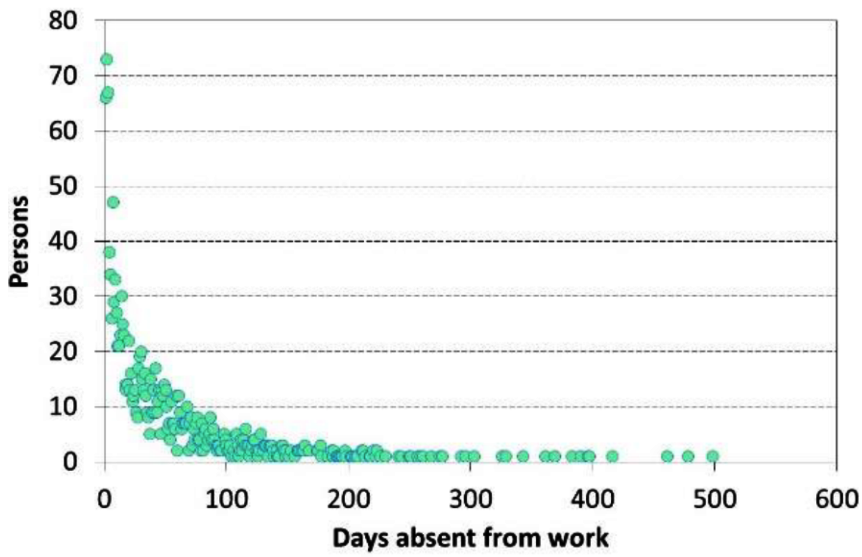


FIGURE 5.11: Workforce Time Lost on the British Mainline (RSSB, 2017a)

Since WTL is usually reported as the number of weeks of absence, to estimate the number of hours lost because of incidents occurring at stations, equations 5.19 and 5.20 can be used:

$$h_{lw} = T_{lw} \times h_{dr} \times I_r \tag{5.19}$$

$$V_{h_{lw}} = h_{lw} \times \omega \tag{5.20}$$

Which could also be obtained using:

$$V_{h_{lw}} = 6I_r \times h_{dr} \times \omega \tag{5.21}$$

Where:

h_{lw} = lost workforce hours (h/yr)

T_{lw} = workforce time lost (weeks/FWI)

h_{dr} = driver's weekly working hours (h/week)

$V_{h_{lw}}$ = value of lost workforce hours (£/yr)

ω = driver's hourly (overtime) pay (£/h)

Cleaning Staff

With PSDs standing between passengers and the rail track, all passenger rubbish stays on the platform and accumulates there compared to the situation without PSDs, where passengers may throw some of this rubbish onto the track, thereby accumulating on the track and requiring clean-up during track maintenance. Either way, trash accumulates, either on the trackside or on the platform, both of which require effort to clean. For this reason, the effect on cleaning staff is considered neutral in this particular case but can be estimated where necessary, using equation 5.22.

A reduction in the amount of paper and fluff in tunnels, thanks to PSDs, limits the cost and risk involved in cleaning these areas and in removing waste materials. London Underground, for example, suffers from small fires in tunnels due to flammable waste being ignited by arcing from the third / fourth rail, leading to service interruptions (personal communication from F. Schmid, 2020). However, the cost and benefit of eliminating most such fires have not been identified.

Platform Staff

There may be fewer staff patrolling PSD-fitted platforms, compared with platforms without PSDs, as they are comparatively safer. That being the case, PSDs reduce staff need on the platforms. However, there are incidences when PSDs fail due to reliability issues; in those scenarios, the particular door set having a fault would have to be manned to ensure manual opening, closing or isolation of the doors depending on the fault experienced. This may not be frequent, but inarguably adds to the staff requirement for the platform. MTR, for example, has a member of staff on standby solely for this purpose during traffic hours.

Taking these two opposite scenarios of staff requirements into account, the present study concludes that the *platform staff* requirement may in certain cases balance out for cases with and without PSDs, and therefore is treated as neutral. However, in other cases, it would be different for the two scenarios. The effect is therefore subjective and is acknowledged as such in the model which can be adjusted according to the local arrangements by the model user. The estimation would be a function of the annual salary and the difference in the number of platform staff, which may or may not be zero.

Staffing Costs

In aggregate, the staffing cost is the combination of the staff changes due to PSDs (see equation 5.22). However, since only two of these changes are estimated to be significant, the overall staffing cost would be the sum of the two non-zero components (see equation 5.23).

$$V_{st} = V_{st_{DCR}} + V_{h_{lw}} + \lim_{cl \to 0} f(cl) + \lim_{ps \to 0} f(ps) \tag{5.22}$$

$$V_{st} = V_{st_{DCR}} + V_{h_{lw}} \tag{5.23}$$

Where:

V_{st} = cost of staffing (£/yr)

$f(cl)$ = function of cleaning cost (£/yr)

$f(ps)$ = function of platform staff cost (£/yr)

However, the cost of hiring a member of staff is usually higher than their advertised annual salary. It includes other expenses for the employer such as pension contribution, national insurance, taxes, etc.

The employer would also have to give consideration to shift allocation because, for example, in the case of DCR staff, one person cannot cover the whole day, meaning there have to be at least two members of staff for the post. In addition, staff go on leave during the course of the year for various reasons, the most common being sickness leave, public holidays, annual leave, etc., so there has to be further staff to cover the shift full time.

For the compilation of the model, it is deemed a responsibility of the user to estimate these costs and merge them into a number (which includes the average overhead) to be entered against the staff salary cell.

5.3.4 Service Disruption

Whenever an incident happens, the train service along the line becomes disrupted for a period. The length of disruption depends largely on the severity of the incident. If it is a minor incident, the disruption could be minimal, while if the incident is severe, say for example a fatal incident, then the service disruption could be longer as there may be a need to wait for the police protocol to be completed, allowing them to carry out the official assessment procedure on the incident before going ahead with clearing the site, by removing the human body(ies) (and body parts, if any) affected.

From the information obtained about the number of incidents on the LUL network and the corresponding service disruptions, a rate has been estimated for the size of service disruption per FWI of an incident, as given in equation 5.24.

A 14-year LUL incident record was obtained, for the period 2000 to 2013 inclusive (as shown in Table 5.1), leading to an annual average of *39.73 FWI/yr*. In addition, a record of total delay minutes on the LUL was also obtained and used to calculate the annual average delay minutes due to incidents as 3,775 min/year. Therefore:

$$\begin{aligned} R_{sd} &= \frac{\delta_{avg}}{FWI_{avg}} \\ &= \frac{3,775}{39.73} = 95 min/FWI \end{aligned} \tag{5.24}$$

TABLE 5.1: LUL Suicide Record (TfL, 2014b)

Year	Total Number of Incidents	Non-Fatal	Fatal	Total Delay (min)	Delay per Incident (min)
2000	46	11	35	2,626	57
2001	60	15	45	3,285	55
2002	51	19	32	2,798	55
2003	46	11	35	3,673	80
2004	44	10	34	2,947	67
2005	46	10	36	3,598	78
2006	50	9	41	4,518	90
2007	63	21	42	4,842	77
2008	67	28	39	2,907	43
2009	82	40	42	5,358	65
2010	80	39	41	5,315	66
2011	83	46	37	3,363	41
2012	83	37	46	3,952	48
2013	81	36	45	3,663	45
Total	**882**	**332**	**550**	**52,845**	**867**
Average	**63**	**24**	**39**	**3,775**	**62**

Where:

R_{sd} = rate of service disruption (min/FWI)

δ = delay minutes (min/yr)

FWI_{avg} = average record of fatality and weighted injuries (FWI/yr)

To calculate the total delay minutes for a given year for a station, the relationship would be:

$$\delta = R_{sd} \times I_r \tag{5.25}$$

The monetary value of the total service disruption in £/yr can be estimated either by using equation 5.26 or more directly using equation 5.27.

$$V_{sd} = \delta \times \mu_\delta \tag{5.26}$$

$$V_{sd} = 95 I_r \times \mu_\delta \tag{5.27}$$

Where:

V_{sd} = value of service disruption (£/yr)

μ_δ = unit cost of delay minutes (£/min)

In the case of retrofitting, there would be some element of service disruption if the retrofitting work is not carried out exclusively during engineering hours. For a safe operation, usually the screen work needs to be completed for the whole platform length before allowing passengers to board/alight trains.

5.3.5 Lost Customer Hours

Service disruption could lead to other issues such as the loss of fare revenue during the disruption period and the induced lost customer hours (LCH). LCH is a term used by LUL to describe the number of customer service hours that are lost due to an interruption of the transport service.

The term customer hour is used as a measure of the time spent by a customer in the transport system being a passenger. In other words, it is a measure of the duration of travel a passenger experiences, from departure at origin to arrival at destination.

From the information obtained (Table 5.2) via the '*WhatDoTheyKnow*' freedom of information source (TfL, 2014a), the annual average LCH on the LUL network is 485,085 h/yr with an annual average of 43 incidents/yr. But for modelling purposes, an arithmetic relationship has been set based on FWI instead of using the general incident record. This is because FWI is a measure of incident severity, while mere incident record (number of incidents only) does not provide information about the significance or severity of the occurrences, which in turn determines how many of the customer hours would be lost due to that particular incident.

TABLE 5.2: Delay Minutes and Lost Customer Hours (TfL, 2014a)

Financial Year	Total No. of incidents	Total No. of Minutes Initial Delay	Total Estimate of Lost Customer Hours
2003-04	39	2,966	386,625
2004-05	38	3,121	451,222
2005-06	36	2,632	269,340
2006-07	41	4,159	383,888
2007-08	44	3,547	545,767
2008-09	42	4,182	536,057
2009-10	41	4,312	603,169
2010-11	43	4,701	576,223
2011-12	46	3,334	357,803
2012-13	49	3,689	608,246
2013-14	50	3,414	617,596
Total	**469**	**40,057**	**5,335,937**
Average	**43**	**3,642**	**485,085**

Therefore, using the recorded average FWI of 39.73 FWI/yr (see Section 5.3.4), the rate of LCH, R_{LCH}, was estimated thus:

$$\begin{aligned} R_{LCH} &= \frac{h_{lc}}{FWI_{avg}} \\ &= \frac{485,085}{39.73} = 12,209\ hr/FWI \end{aligned} \tag{5.28}$$

Where:

h_{lc} = lost customer hours (h/yr)

This is just an example for the sake of calculation. However, the R_{LCH} equation can be used to estimate the amount of LCH in any year of interest provided the FWI for that year is known. This can be achieved simply from taking the product of R_{LCH} and FWI.

The pecuniary value of LCH is obtained as the sum of fare revenue lost due to the LCH. This is elaborated further in Section 5.3.6. Note that unplanned delays may attract compensation to passengers whose journey exceeds a certain length, e.g., 15 min or above in the UK (DfT, 2018a). However, this may not be relevant for the metro.

5.3.6 Fare Revenue

Fare revenue is one of the key financial sources for transport services, not just the railway. The revenue is generated by collecting travel fares from passengers, which is made possible only when trains are running. In situations where there is a disruption to the service, the fare revenue would reasonably be assumed to halt until the service is back up and running.

An estimation has been carried out for the fare loss owing to service disruptions that lead to LCH based on the proportional relationship between the fare and the LCH (shown in equation 5.29). The longer the service disruption, the more passengers do not travel, and the more fare revenue lost. thus:

$$V_{fr} = \frac{60}{\bar{J}}\left(h_{lc} \times f_0\right) \tag{5.29}$$

Where:

V_{fr} = value of fare revenue (£/yr)

$\bar{J}$ = average journey length (min/journey)

f_0 = single journey fare (£/journey)

Equation 5.29 yields an estimated fare revenue lost in a certain year. For comparison between the case with PSDs and the case without PSDs, the fare revenue difference comes from the estimated reduction in LCH where the presence of PSDs averts some accidents at the station under question. If the expected LCH differ with and without PSD scenarios, the difference would be turned into the addition or reduction of lost fare revenue.

5.3.7 Platform Space

Many station platforms have yellow safety lines or equivalents near the edges of the platforms to indicate the limit within which it is safe for passengers to stand while waiting for a train to arrive. This isolated area reduces platform space as it runs the full length of the platform. The yellow lines or equivalent are provided for safety reasons, with the aim to keep passengers well back from the platform edge (Hirsch, 2008). The yellow safety lines are sometimes inscribed with braille blocks having embossed points/lines (Fujita, 2016) thereby serving the purpose of safety not just by visibility, but by texture as well, so that passengers who are visually impaired may find it as useful.

However, on PSD-fitted platforms, the safety lines become unnecessary due to the provision of a barrier that prevents passengers from falling off the edge. As such, the platform edge area marked unsafe for passengers can now be used, thereby increasing the platform space.

In a relatively recent research on PTI, Fujiyama and Seriani (2016) claimed that on platforms where PSDs are not installed, the first passenger row at the platform edge (demarcated by the safety lines) is less used during the boarding and alighting process, in comparison with situations with PSDs. They demonstrated with interaction maps (Figure 5.12) that the platform edge area is much more useful in the presence of PSDs. This is evidence that the deployment of PSDs increases platform space by providing more usable space to accommodate passengers, while mitigating the risk of the platform edge as acknowledged by Hirsch *et al.* (2007).

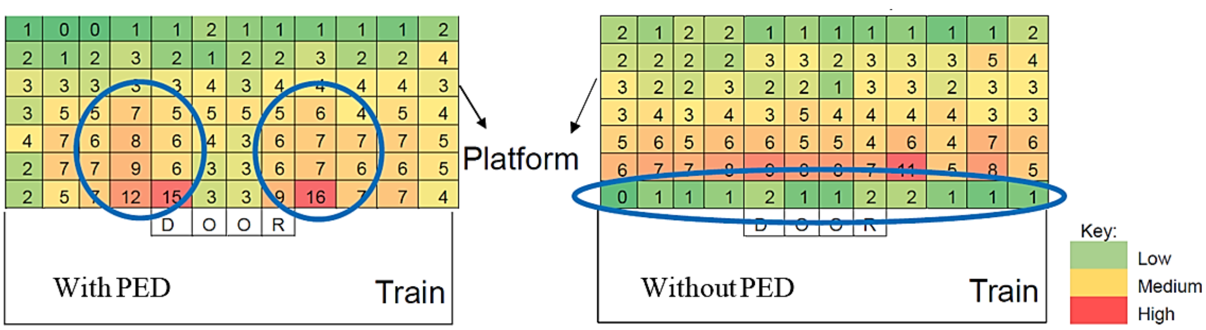


FIGURE 5.12: Platform Interaction Map (Fujiyama and Seriani, 2016)

Nevertheless, the PSDs themselves occupy space on the platform edge where they are installed, no matter how little. For a fair assessment of how much space is released to passengers by the presence of the PSDs, this space occupied by the PSDs is also taken into consideration as illustrated in Figure 5.13. With this, the increase in platform space can be estimated using equations 5.30 and 5.31.

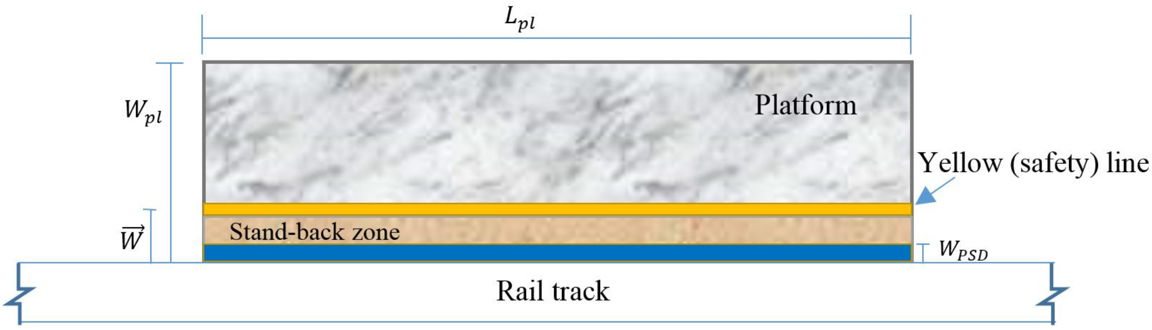


FIGURE 5.13: Platform Space Released to Accommodate PSDs (Author)

The layout differs from one system to another. For instance, in some systems the stand-back zone is all in yellow, but layouts all serve the same purpose of alerting the passengers to stand back from the platform edge to minimise the risk of accidental fall and the impact of wind surge as trains pass through the platform.

The platform space gain can therefore be estimated thus:

$$C_{pl} = \rho\left(\bar{W} - W_{PSD}\right)L_{pl} \tag{5.30}$$

$$^{\%}C_{pl} = \frac{\bar{W} - W_{PSD}}{W_{pl} - \bar{W}} \tag{5.31}$$

Where:

C_{pl} = platform space increase (persons)

ρ = standard passenger density (persons/m^2)

$\bar{W}$ = stand-back width (m)

W_{PSD} = PSD width (m)

L_{pl} = platform length (m)

$^{\%}C_{pl}$ = percentage increase in platform space (%)

W_{pl} = platform width (m)

An increase in platform space means that the platform can accommodate more passengers. This may not be significant for most platforms but can be a benefit at densely populated platforms at peak periods. It could relieve the passenger crowd, thereby reducing discomfort (Kroes *et al.*, 2014) depending on how much of the platform space is provided. Although the effect on platform space is not financially estimated in this study, it is something that decision makers would need to be aware of and take into account in their planning. This is, however, a small benefit.

5.3.8 Air Quality

The presence of PSDs causes a change in the quality of air on the platform. This is through retaining the carbon dioxide (CO_2) exhaled by passengers on the platform, holding back any radon rising from the track area, and averting particles coming onto the platform from the trackside. These particles, usually called PM, are of various categories, namely PM_{10}, PM_5 and $PM_{2.5}$. PM_{10} for example refers to particles that are 10 micrometres in diameter or less, PM_5 for particles that are 5 micrometres or less, and so on.

The air quality is important because it can directly or indirectly affect human health conditions (Wade, 2018; Watkiss *et al.*, 2006) when inhaled, especially on a regular basis. The deployment of PSDs, therefore, can affect platform air quality by inducing a change in the quantity and flow of the following:

1. Particulate matter (PM)
2. Radon level (Rn)
3. Nitrogen oxides (NO_x)
4. Carbon dioxide (CO_2)

The value of change in air quality could simply be an algebraic sum of all the products of the pollutant damage cost and the change in the quantity of the pollutant (equation 5.32). This should be considered in cases where the pollution exceeds the workplace exposure limit in compliance with respective regulation such as the Health and Safety Executive (HSE) regulation EH40/2005 in the UK that states an exposure limit of 4 mg/m^3 for an 8-hour exposure to respirable dust (HSE, 2018), or in the case of NO_2, a legal limit of 40 $\mu g/m^3$ (Wade, 2018), etc.

$$V_{aq} = \sum_{p=1}^{n} \left(DC_p \times \Delta_p \times \aleph \right) \tag{5.32}$$

Where:

V_{aq} = value of change in air quality (£/yr)

DC_p = damage cost of (any) pollutant, p (£/person-yr/unit quantity, e.g., £/person-yr/$\mu g/m^3$)

Δ_p = change in the quantity of pollutant, p (quantity, e.g., $\mu g/m^3$, tonne, etc.)

$\aleph$ = average number of staff exposed daily (staff/platform)

For instance, unit A 3.2 of the UK WebTAG Databook (DfT, 2018c) reports values particularly for PM_{10} and NO_x pollution as in Table 5.3.

TABLE 5.3: Air Pollution Damage Cost (2018) Values by Pollutant (DfT, 2018c)

	Central Value	Low Value	High Value
PM_{10} (£/household/$\mu g/m^3$)	117.7	61.7	133.7
NO_x (£/tonne)	1,199	934	1,362
NO_x marginal abatement cost (£/tonne)	33,026	30,748	83,134

As the average household occupancy in the UK is 2.4 person/household (Knipe, 2017), the values of PM_{10} per person can be estimated by simple division of the household damage cost (a low value is used here) by the household occupancy size, thus:

$$DC_{PM10} = \left(\frac{61.7}{2.4} \right) = 25.71 \ \ \pounds/person - yr/\mu g/m^3 \tag{5.33}$$

This can be applied to platform scenarios to quantify the little benefit stemming from air quality improvements using an estimated change in PM_{10} due to the presence of PSDs, taking into account the number of staff working on the platform[3].

The platform air quality estimation procedure can also be used in the context of on-board air quality, particularly for the tunnel PM that accumulates on board trains as shown in Figure 5.2.

5.3.9 Train Noise on the Platform

Train noise on the platform is related to the quality of announcements described in Section 5.5.2. Train noise not only interferes with announcements, it also poses a form of disturbance to passengers which can be unpleasant. Passengers waiting for trains have to speak up to be heard correctly when there are trains on other platforms.

The noise effect on passengers is normally of short duration, whereas for platform staff it repeats every time trains pull in and out, creating a risk of Noise-Induced Hearing Loss (NIHL) (Gershon *et al.*, 2006).

Noise is considered by the World Health Organization (WHO) to be a factor of environmental risk for poor health. Long-term noise exposure can be a serious threat to public health, causing problems such as (Wade, 2018; Wang *et al.*, 2017):

1. Psychological problems
2. Episodic memory problems
3. Obesity problems
4. Children's blood pressure issues
5. Cardiovascular diseases
6. Temporary or permanent hearing problems
7. Effect on performance
8. Change in sleep patterns
9. Anxiety, stress and aggression, etc.

Other non-health problems that can be caused by noise exposure include disturbance (or discomfort) and an effect on communication.

[3] Passengers are discounted because they only stay on the platform for a few seconds/minutes to board a train.

An acceptable noise level that is generally considered to cause no harm is one which is below 70 A-weighted decibels (dB A) regardless of the duration of exposure (Wang *et al.*, 2017). Anything above that has potential to cause harm when exposure duration is long. This is because noise dB are logarithmic in nature which means that an increase of 10 dB, for instance, equals a 10-fold increase in intensity. To enable a practical understanding of the magnitude of noise measurements, Table 5.4 was prepared according to the technique of Gershon *et al.* (2006).

TABLE 5.4: Noise Levels in Practical Situations (Gershon *et al.*, 2006)

S/N	Situation	Approximate Noise Level (dB A)
1	Whisper	30
2	Normal conversation	45-60
3	Chainsaw	100
4	Train in subway	80-120
5	Gun blast	140

Platform style (side or island) and station location (underground or above ground) can have an effect on the train noise level experienced on platforms. Above ground stations usually have an average noise level about 6.4 dB lower than that of underground stations (Soeta and Shimokura, 2012).

Railway noise transmission comes from wheel-rail interactions, brake noise and from the train traction. These can all be reduced by PSDs (Qu and Chow, 2012; Wang *et al.*, 2017) through diffraction and reflection by the glass surfaces. Half-height APGs have also been proven to reduce noise level in underground stations, but not by as much as full-height PSDs (Soeta and Shimokura, 2012; Wang *et al.*, 2017). The platform noise distribution is shown in Figure 5.14.

For noise to be considered harmful, subjects would have to be exposed for a long time. For example, the recommended exposure limit for noise up to 90 dB is 8 hours with hearing protection, 15 minutes for noise up to 100 dB, etc., (Taylor, 2013). Hence, harm

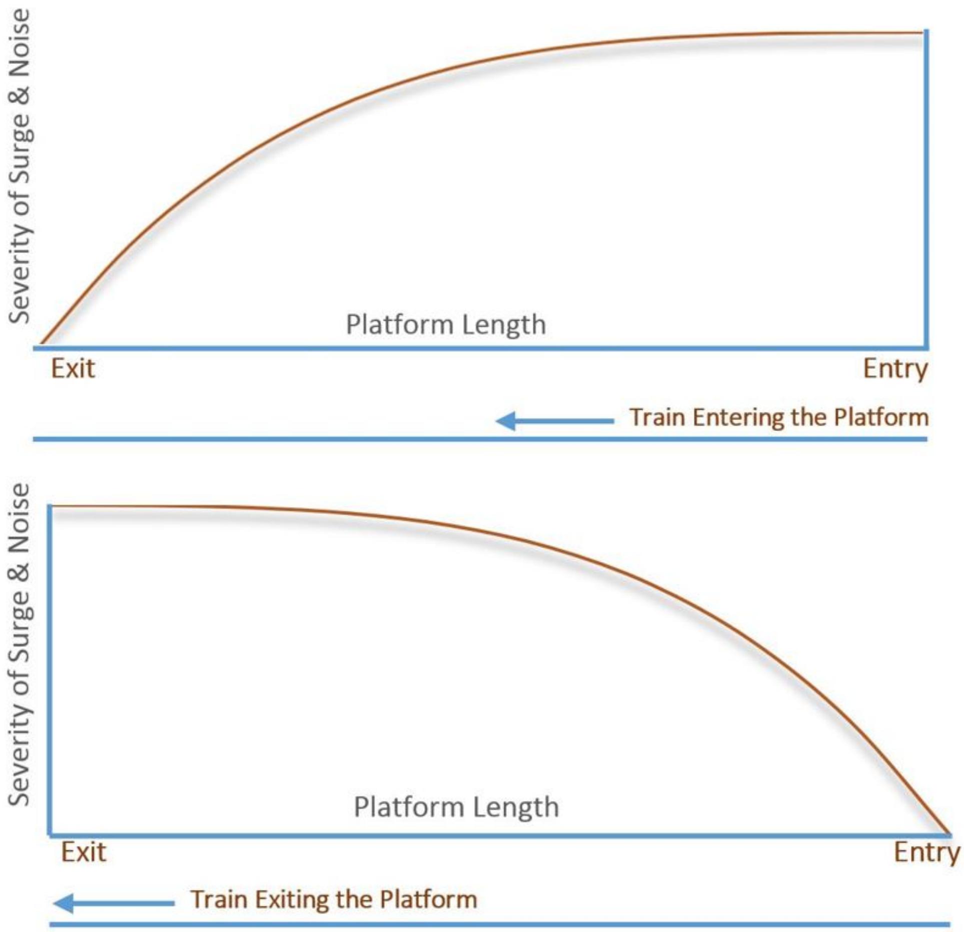


FIGURE 5.14: Distribution of Wind Surge and Train Noise (Author)

due to platform noise is likely to affect only staff working on the platform. Passengers would only be on the platform for a few seconds/minutes in order to board the train, but platform staff would be exposed to repetitive noise throughout their shift. Therefore, the value of any change in platform noise level due to PSD deployment is estimated based on the number of platform staff, using equation 5.34.

$$V_{noise} = \eta \times \Delta_{noise} \times \aleph \tag{5.34}$$

Where:

V_{noise} = value of change in platform noise (£/yr)

η = marginal value of noise annoyance (£/dB-person-yr)

Δ_{noise} = change in the platform noise level (dB)

5.3.10 Line Capacity

Railway capacity refers to the ability of the railway to transport certain number of passengers from origin to destination using certain number of trains over a certain period of time (Connor, 2017). Capacity often depends on *train frequency* which is usually expressed in terms of trains per hour (tph).

Efficient use of capacity is crucial to the success of a railway system and is usually determined by the timetable schedule and largely dependent on the technical characteristics of the infrastructure and rolling stock. However, there are certain factors affecting rail capacity as extracted from Connor (2017) and summarised in Table 5.5.

TABLE 5.5: Factors Affecting Capacity (Author's formulation after Connor (2017))

S/N	Operating Conditions	Infrastructure	Train Performance	Other
1	Degree of automation	Control (signalling) system	Interior design	Weather condition
2	Recovery margins	Station spacing	Length	
3	**Station dwell times**	Maximum line speed	Train control	
4	Speed restrictions	Terminal design	Acceleration	
5	Terminal operations	Available power	Braking rate	
6		Gradients		

PSDs can affect dwell time by changing various components (see Figure 5.15) of the static aspect (doors opening and closing time), and through the time taken to interlock with the trains upon arrival and disengage before departure. These in aggregate escalate to affect the line capacity as affirmed by Lindfeldt (2017) through a RailSys simulation.

However, PSDs can also have a positive impact on the dynamic component of the dwell time through improvement of passenger behaviour at platforms, leading to more organised boarding and alighting processes (Rodríguez *et al.*, 2016), which by extension leads to a faster and hence shorter dwell. Other factors influencing boarding and

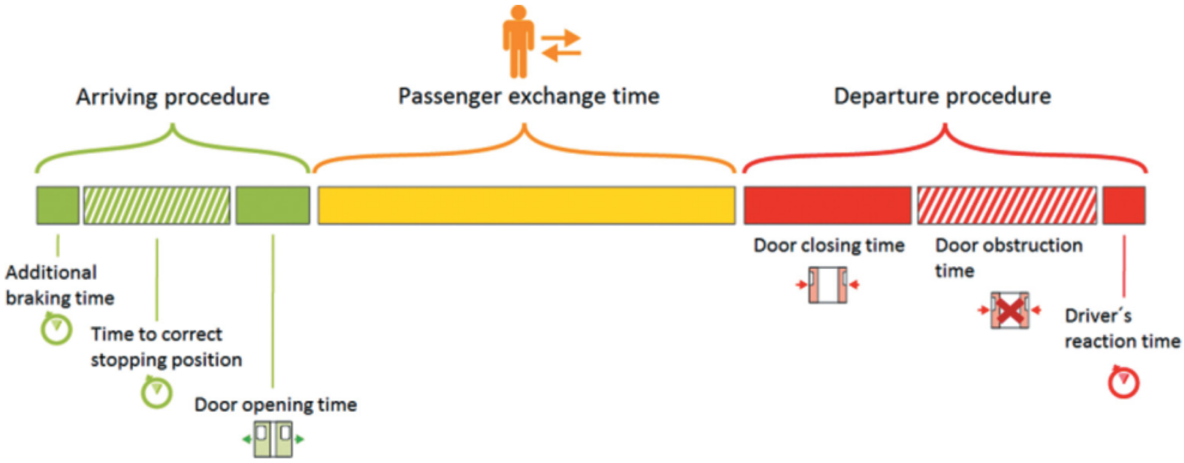


FIGURE 5.15: Components of Dwell Time (Lindfeldt, 2017)

alighting time include vertical and horizontal gaps at the PTI between the platform edge and the train.

Given that there is a benefit from managing joining and alighting better, the longer dwell times caused by the trains having to interface with the signalling controls and door slots may reduce the number of paths, and thus overall capacity. For example, if you build a metro line for £1 billion and end up with 24 paths in the peak hour rather than 25, it will have an impact of -1/25 (which in this case is a 4% reduction) on the capacity. This will negatively affect the overall BCR of the project. The magnitude of impact on the BCR would be aggregated with other positive and negative effects to yield an overall value as further elaborated in Section 6.4.2.

The importance of minimising dwell time can therefore not be over emphasised. It is the main cause of the recent dispute about door opening and closing by drivers instead of guards on the South Western Railway (SWR) in the UK. This resulted in strike actions by the National Union of Rail, Maritime and Transport Workers (RMT) (Purley, 2020; Dickens, 2019). The SWR is looking to increase capacity by reducing the processes involved in opening and closing of doors which was being handled by the guards. SWR wanted drivers to be doing that instead in order to decrease dwell time, hence increasing capacity. The RMT, on the other hand, sees this as a way of getting rid of the guards and therefore opposes the move, leading to strike actions.

This is not the only example where the capacity issue dominates the majority of talks around a railway service. Another example is the Tyne and Wear (T&W) Metro in the UK which has gone a long way to strategise replacement of its old fleet as the feasible option to increase frequency of service. This was estimated to cost somewhere around £300 million (Hughes, 2017).

Considering this importance of dwell time, the author has weighted the effect of PSDs on capacity through a series of mathematical derivations expressed in Equations 5.35 through to 5.41, starting with the change in dwell time, thus:

$$T_{nh} = T_{ch} \pm \Delta d \tag{5.35}$$

Where:

T_{nh} = new headway (sec)

T_{ch} = current headway (sec)

Δd = change in dwell time (sec)

But,

$$\lambda = \frac{3,600}{T_h} \tag{5.36}$$

Where:

λ = line capacity measured in terms of train frequency (tph)

T_h = headway (sec)

Therefore, the *new* train frequency, λ_n, would be:

$$\lambda_n = \frac{3,600}{T_{ch} \pm \Delta d} \tag{5.37}$$

Furthermore, the percentage *change in capacity* would be a function of the current and new frequencies, thus:

$$\Delta\lambda = \left(\frac{\lambda_c - \lambda_n}{\lambda_c}\right) \times 100\% \tag{5.38}$$

This can similarly be obtained using equation 5.39:

$$\Delta\lambda = \left(1 - \frac{3,600}{\lambda_c(T_{ch} \pm \Delta d)}\right) \times 100\% \tag{5.39}$$

Where:

$\Delta\lambda$ = change in line capacity (%)

λ_c = current train frequency (tph)

Having obtained the change in line capacity, the number of trains removed (or added if the dwell time is shortened) is then estimated using equation 5.40:

$$n_t = \Delta\lambda \times \lambda_c \times h_{op} \tag{5.40}$$

Where:

n_t = number of trains removed (if negative) or added (if positive) (train/yr)

h_{op} = annual station operation hours (h/yr)

If the possibility of running more trains arises or the possibility of taking some trains off the schedule emerges, the passenger-carrying capacity would also be affected and can be estimated as a multiple of average train occupancy and the number of trains removed or added. This can then be multiplied by the average single journey fare to get the pecuniary gain or loss due to the effect of PSDs on capacity (see equation 5.41).

$$V_\lambda = \frac{1}{n_p}\left(n_t \times C_{max} \times \bar{C}_r \times f_0\right) \tag{5.41}$$

Where:

V_λ = value of capacity (£/platform-yr)

C_{max} = maximum train capacity (p/train)

$\bar{C}_r$ = average (train) riding occupancy (%)

f_0 = single journey fare (£/passenger)

n_p = number of train stops (platform)

5.3.11 PSD Equipment and Installation Costs

The cost of purchasing and installing of PSD system is usually merged in the contract agreement between the client and the PSD manufacturer. It is mostly quoted in terms of cost per linear metre of screen work. This usually involves all other cost components such as trial (off-site) installation, delivery to site, on-site installation, testing, integration and commissioning, etc.

However, depending on the contract terms and conditions, there may be other additional expenses such as that of running trial trains, and other platform modification costs which are likely to be significant in the case of retrofitting.

From the information provided in confidence by Consultant Engineers 1 and 2, the production cost for the doors alone is approximately 20% of the whole contract cost, the rest being for the design, prototype, other materials (or components), installation, integration and dynamic testing, although this may vary from contract to contract and may differ between say Asia and Europe where the size of the market is very different. The cost is also likely to be influenced by the type of doors (full-height or half-height) and by any optional functions incorporated such as those discussed in Section 5.5.13.

For the purpose of this study, inquiries were made to find out the cost of installing PSDs. Different projects have different costs, but mostly around an equivalent of £3,000,000 per platform or nearly £13,000 per linear metre, as is the case for one of the most recent PSD installations[4]. However, the PSDs installed on Seoul subway (completed in 2009) were installed at a much higher cost (Sawada *et al.*, 2015) equivalent to just under £35,000 per metre, when converted to the present (2020) value. Details of the project available to public is not sufficient to understand why it costed that much.

The author has obtained four different costs of PSDs from four different projects and took an average (£18,774 per metre) to be the default value in the model. A space is also provided in the model for direct input of the (known) PSD cost per linear metre

[4]Trusted confidential source.

of screen work to replace the default value. Hence, there is no need for further mathematical derivations.

5.3.12 PSD Maintenance Cost

The maintenance cost of PSDs is another cost component which needs to be included in any evaluation. Even though most modern PSDs require little maintenance, the expenses accumulate over their lifetime. The common practice is to award a maintenance contract to (usually) the supplier of the equipment or to do it in-house.

Maintenance of the moving parts, such as the *door pins* for the door lock mechanism and other active parts, such as the *door rubbers*, may be required frequently and they may require replacement from time to time, depending on the failure rates and reliability of the system. There is usually an additional cost for half-life overhaul of the whole system.

Just like the installation cost, the maintenance cost has an input in the model for the user to key in an estimate of the annual maintenance cost. As a default value, an average of the maintenance costs obtained for three PSD projects was taken and it is about 2% of the installation cost per year, i.e. £357 per metre per year. All default values are shown in Appendix B; Figure B.1.

5.3.13 Rolling Stock Limitation

One of the key drawbacks associated with PSDs is their restrictive or fixed structure that allows only a certain type of rolling stock to be used. This is due to the fixed door positions beyond which are solid screen walls, making it quite impossible for certain geometries of rolling stock to synchronise train door positions with the screen door positions, creating an issue for compatibility (Qu and Chow, 2012).

A senior rail industry source, one of the stakeholders in the UK Thameslink project, indicated that this particular drawback of PSDs is the main reason that informed the decision not to incorporate them in the central London stations where 24 trains an hour are planned.

However, on most metros with homogenised fleets this is not a problem. If an existing line is being converted, rather than building a new one, it would possibly have to be closed totally for several months while withdrawing the old trains and then test and do system integration for the new ones.

The rolling stock limitation is not quantified because of its unpredictable nature which can vary from one system to another, but decision makers have to be aware of it and think carefully about its short- and long-term effects.

Short-Term Effect

In the case of train breakdown, there will be need for replacement train(s). With the presence of PSDs, the replacement trains must conform to the fixed PSD geometry, otherwise they cannot be used. This limitation would reduce interoperability, restrict the chance of cascading trains and generally cause a lack of flexibility across networks.

Long-Term Effect

In the long term, the rolling stock limitation to future trains on the line may not be so problematic. If there is a need to replace all or some of the trains for any reason, specifications can be given to the train manufacturers according to the existing PSD geometry for conformity which should not involve any extra cost. However, there would still be an impact on the operational flexibility.

5.4 Neutral Factors

From all the factors identified as being affected by PSD deployment, the following were identified by the research but after review were considered to be neutral and therefore not quantified, as shown in Figure 5.8 based on the reasons given in the respective sections below. However, the neutrality of these factors applies by default in the generic model, but for specific cases where the user identifies a quantifiable importance of these factors, they can be estimated and incorporated into the model.

1. Touch Voltage
2. Aesthetics/Attractiveness
3. Emergency Evacuation

5.4.1 Touch Voltage

When a person encounters an energised object, there is a difference in voltage between the feet of that person and the point of contact with the object, due to the potential difference between the two points. This is termed touch voltage, and it is a potential hazard for electric shock which can lead to serious injury or fatality (Tokai-Omni, 2014). Touch voltage is typically present at platforms, around the rails and at traction power substations (Pham *et al.*, 2003). However, Sim *et al.* (2005) suggest that platform touch voltage occurs only under a fault (short circuit) condition. For passengers on a platform, there are three main scenarios (Tokai, 2017) through which they can experience the touch voltage:

1. While boarding and alighting,
2. During an encounter with the PSD frames, and
3. Encountering the train body.

Platforms, being places for passenger crowds, require prevention against touch voltage risks through a few protective countermeasures, the most common ones being the isolation and limitation approaches, both of which are well explained by Sim *et al.* (2005). Isolation is carried out using a membrane on the platform surface (Maxbond, 2018) to serve as insulation, safe-guarding passengers from incidents of touch voltage. The limitation approach, on the other hand, addresses the rise in potential (usually equalising) between conductive surfaces.

With the presence of PSDs, the metal elements of the doorframe can also transmit such issues to passengers touching them, and with proximity to the train they together create an area posing the highest risk to electric shocks associated with touch voltage. However, the glass surfaces of PSDs do not conduct electricity and serve as insulators to the passengers on the platform, separating them from the metal surfaces of the dwelling train.

Touch voltages are strongly influenced by earthing of the electrical appliances and equipment around the PTI, and there are usually two types. One is for the station appliances, called station earthing, and the other is for the tracks, called traction earthing. Earthing of the PSDs can be bonded to either of the two, but with effective measures to avoid incidents of touch potential.

TABLE 5.6: Risks Associated with Touch Voltage at PTI (Author)

	PSDs to Station Earth	PSDs to Traction Earth
People on Platform	No Risk	Risk
Boarding/Alighting Passengers	Risk	No Risk

The effect of PSDs regarding touch voltage can therefore be difficult to examine because it has both positive and negative impacts on either of the earthing choices (see Table 5.6). Hence, the current research assumes such an effect as neutral.

5.4.2 Aesthetics/Attractiveness

With PSDs, platforms generally have more or less a modern look, better indoor environment (Qu and Chow, 2012) and the potential to derive pleasure, making travel slightly less boring for the passengers, especially when adverts are displayed to a reasonable level on the screen panels. This is usually the case with *'side platforms'* where in the absence of PSDs, is just a wall that passengers see as they wait for the arriving train. It can therefore be argued that the aesthetics of PSDs could attract more passengers to railway transport.

Despite their attractiveness, the author suggests that PSDs may in certain circumstances become an unwanted hindrance. For example, in stations where a series of island platforms are in place, there exists a view across platforms which may be pleasurable to some passengers by giving them chance to see over to other platforms as far as their vision allows, making them feel less confined and less restricted in what they see. But this entirely comes down to personal preference; another group of passengers may find having the view of just the platform they are on (such as in the case with PSDs) more attractive and pleasing.

In the case of half-height PSDs, the author is of the opinion that aesthetic pleasure could be combined, i.e. allowing both cross-view and a view of the PSD aesthetics. But it could also have a negative effect on both scenarios, especially for passengers whose height corresponds to that of the PSDs, thereby causing confusion on where to focus their vision – to the platforms across the track, or just on the PSDs, having some vision conflicts at the top edge of the PSDs.

The issue of Aesthetics/Attractiveness is therefore subjective and is considered neutral (having both positive and negative sides as in Figure 5.16), so its statistical value has not been estimated.

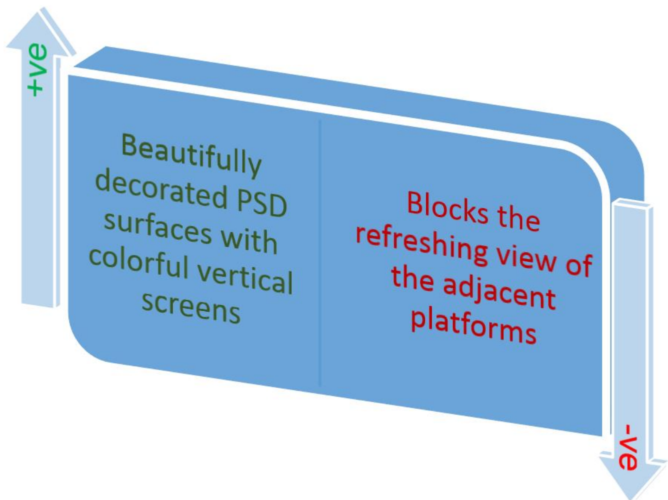


FIGURE 5.16: Aesthetic Effects of the PSDs (Author)

5.4.3 Emergency Evacuation

Emergencies can happen suddenly without any preparation. It would be undesirable to come across a barrier while trying to get people out to safety in those emergencies. Tunnel fire can happen for many reasons, including overheating of brakes and arson attack (Bilge, 2018). In such a case, platform doors could act as a hindrance to the on-board passenger evacuation process.

In an event where there is (say) a fire on a train as it comes through a station, the evacuation process would be expected to start immediately. On platforms where PSDs are fitted, and if they malfunction for some reason, e.g., loss of power, they can delay the (on-board) passenger evacuation process. In such situations, the ERM, which is a manually operated mechanical lock (see Appendix C.6) of the PSDs, would have to be operated by passengers to get out.

Eventually, the platform staff may manually open the emergency doors (mostly located at both ends of the platform or along the platform length) to facilitate the evacuation process. Nevertheless, this may still affect the *safe egress time* for a large number of passengers (Qu and Chow, 2012).

On the other hand, the presence of PSDs could be a positive thing in the event of an emergency incident occurring on the platform. If there are many passengers on the platform when the emergency starts, and people are required to evacuate, there is a possibility they will move in random directions, creating chaos. Therefore, there is a danger of passengers being pushed to the trackside (if there are no PSDs) due to overcrowding; they may be struck by trains coming into the platform, passing trains, or be electrocuted by any electricity-carrying rails. PSDs could mitigate this, thereby controlling passengers and preventing them from such risks.

It can therefore be seen that the deployment of PSDs could be either harmful or beneficial in an emergency depending on where the emergency incident is and how it develops (see Table 5.7). If it is from the tunnel (or from the trains), then PSDs could have a negative impact on the people on board and positive impact on people on the platform. If the emergency initiates from the platform (or somewhere in the station), then PSDs offer a positive protection against risks of falling onto the tracks and help prevent passengers arriving in trains.

TABLE 5.7: PSD Effect in an Emergency (Author)

	Fire in Tunnel	Fire on Platform
People on Platform	Positive	Positive
People on Train	Negative	Positive

5.5 Immaterial Factors

There are factors which have been identified but are not considered by the researcher to be significant to the overall economic analysis of PSDs. They were captured in the CLD in order to show the overall effects of PSDs on the rail system, but they were not estimated for financial purposes due to the fact that they are highly unlikely to amount to any significant value that could change the final outcome to support a PSD deployment decision. The author has defined these factors as *'immaterial'* for the purpose of this analysis. However, for a case where a particular system sees them as significant, they can be valued and incorporated into the executable model through the extra cells provided for any additional parameters. For this thesis, however, they have been roughly estimated and found not to be significant (see Appendix D). The factors are:

1. Need for staff training
2. Sound quality of platform announcements
3. Wind surge
4. Trash on the line
5. Sense of security for the waiting passengers
6. Rate of smoke spreading from tunnel to platform

7. Service reputation
8. Passenger shock/trauma
9. Train delays and cancellations
10. Customer satisfaction
11. Disutility of travels
12. Service reliability
13. Optional PSD functions:
    (a) Gap closing
    (b) LED lights
    (c) Heating/cooling
    (d) Media, e.g.,
        i. Passenger information screen
        ii. Advert and announcement potential

5.5.1 Staff Training

When PSDs are deployed for the first time, there is a need to train staff on door control, particularly those manning the DCR, if any. The training would take place at the beginning of deployment, and perhaps periodically and on demand when new staff are employed, predominantly maintenance staff.

The training would incur some costs if external tutors are to be used. This is likely to be the case for the initial training. However, for future training, the in-house staff would ideally train newer staff as they assume their duties, in which case the expenses for the training, if any, would be negligible. It may also be the case that the PSD contract involves staff training, hence there being no additional expenses for training.

Whichever the case, the cost of staff training would be negligible and is therefore considered insignificant to the overall estimates for making a decision as to whether to deploy PSDs. It is, however, incorporated in the estimates for *staffing* (see equation 5.18).

5.5.2 Sound Quality of Platform Announcements

Platform announcements are often obstructed by the frequent noise of incoming and outgoing trains, rendering these announcements less effective and less heard by the passengers on the platform. This interference would be slightly lower with PSDs which would block a portion of the train noise even though berthed trains have their doors wide open, but they are stationary and do not emit significant noise, unlike moving trains. This is why the effect on the quality of platform announcements is also considered insignificant.

5.5.3 Wind Surge

Passengers standing on a platform without PSDs normally experience a wind surge when a train pulls in, creating discomfort due to the velocity and pressure of the air (Abi-Zadeh, 2003; Hur *et al.*, 2004). The transient pressure would depend on the position in which the passenger is standing on the platform as well as the piston effect generated from the train speed and the cross-sections of tunnels in case of underground railways.

Stopping trains would normally pull in at a relatively higher speed at the point of entry than at the point of exit. Hence, passengers standing near the entry would experience a higher transient pressure compared to those in the middle of the platform and to those at the other end of the platform; the pressure decreases along the platform length. Conversely, when the train is leaving the platform, the transient pressure reverses, being higher at the exit point and lower at the entry. This phenomenon is similar to that of train noise for both incoming and outgoing trains and is illustrated in Figure 5.14.

Depending on the severity of the surge, it can lead to passengers or luggage being dragged (Zhou *et al.*, 2014). This is a safety concern. But with PSDs, the wind surge is partly or completely suppressed, depending on the height of the doors (Zhang *et al.*, 2012), thereby increasing passenger safety and comfort. Full-height PSDs virtually eliminate the surge, whereas half-height PSDs may reduce it to a tolerable and often unnoticeable level as is the case for the Taiwan's half-height PSDs that are designed to withstand a wind speed of 210 km/hr (Ramasearmy, 2017).

5.5.4 Trash on the Line

On platforms without PSDs, there is a risk of litter building up on the rail lines around the platform. This is dependent on passenger behaviour and the availability of trash bins in close proximity on the platforms. Some passengers do have a habit of dropping litter on the floor or throwing it into the track area instead of politely using the dustbins provided, if any. This can happen due to several reasons, including:

1. Non-availability of dustbins.
2. Carelessness or (for children) childish behaviour.
3. Non-strategic locations of the dustbins.

Litter that is dropped onto the platform floor can be pushed into the track area through passenger movements and can gather in similar places. This, over time, can become considerable amount that may be harmful to the rail track and have an effect on the wheel-rail interaction, creating either additional unwanted friction or establishing a slippery surface with less friction, thereby affecting train acceleration, deceleration and/or breaking rates.

According to the 1994 rail regulation (ORR, 1994), depending on the type and amount of litter piled up, it can become a safety or fire hazard and sometimes a security concern (RSSB, 2017c). It can also lead to the possibility of derailment, rail rust, accelerated rail wear, etc.

However, only a few railways are reported to have a challenge with solid waste generated by passengers, notably Indian Railways (Sridhar and Vengal, 2015) that are calling for an efficient waste management system. Nevertheless, PSDs, when present, would reduce the amount of trash that goes onto the tracks from the platform, keeping the trackside litter-free and safer. But the alternative to platform trash not being pushed by passenger movement onto the line is it remaining on the platforms, making them untidy and requiring more cleaning.

In summary, PSDs can prevent trash falling onto the tracks, and by doing so enabling litter build-up on the platforms, making their trash-related effect insignificant.

5.5.5 Sense of Security for Waiting Passengers

Open platforms can cause passengers to feel unsafe with a fear of falling onto the tracks, especially during rush hours when platforms are crowded. This is common during peak periods in busy LUL stations. In most instances, boarding becomes more or less like a queuing process where passengers closer to the platform edge board the train, and those immediately behind them are pushed by the passengers entering the platform. In most cases, passengers at the edge would have to exert some sort of pressure to maintain their position as they wait for the next train.

This feeling of potential harm and having to resist pushing is eliminated by PSDs, thereby making passengers feel secure even if they are pushed to the PSD surface due to high passenger density. In addition, cases of assault (passengers being deliberately pushed onto the track) are also avoided by PSDs.

This feeling of potential risk has not been quantified in any transport-related appraisals, which led the author to consider it immaterial to the overall analysis.

5.5.6 Rate of Smoke Spreading from Tunnel to Platform

In the event of fire, the most dangerous threat to life is usually not direct exposure to the fire but the inhalation of smoke (Li and Zhu, 2018). This is because smoke contains toxic gases and hot air which can cause death by suffocation. As such, the containment of smoke during fire outbreak is of paramount importance.

In relation to fire from a tunnel, PSDs where present can serve as a barrier to smoke spreading to platforms and eventually to the wider station area. Roh *et al.* (2009) proved using a Fire Dynamic Simulator (FDS) that the rate at which the smoke spreads with PSDs is lower than that in cases without PSDs, giving passengers on platform more time to evacuate. Therefore, PSD deployment would have a positive but not significant effect in this case, since tunnel fires are not frequent and, when they do occur, there is a likelihood that PSD door sets would be wide open to aid evacuation of on-board passengers.

5.5.7 Service Reputation

Service reputation is largely dependent on the overall performance of the system. However, in relation to PSDs, it can be associated with the level of satisfaction the customers have considering issues such as the safety and security of the system through PSD intervention in platform incidents, disruption of service caused by the platform incidents, etc.

5.5.8 Passenger Shock/Trauma

Just like the workforce involved in incidents, passengers who witness incidents can suffer from the traumatising experience. However, passenger trauma is not usually estimated due to its complexity. Rail operators have information about their workers but not much about their customers, leading to difficulty in determining how many passengers witness incidents and following up to see how they cope with the shock/trauma.

This research recognises the existence of passenger trauma even though it is not estimated, for numerous reasons, among which are its relevance to decision-making, and the complexity of estimating it without having an account of how many people were able to see the incident when it occurred, how many of those were traumatised and to what extent, etc. It entails identification of the affected population, follow-up with their conditions post-incidents and the cost involved for counselling which is often a social cost.

An example of this is the Leicester Square station accident in London, where a person was hit and killed by a train arriving into the station on the Northern line of the London Underground network (Loveridge-Greene, 2018; Anglesey, 2018). There were many passengers on platform (Grafton-Green, 2018) waiting to board the train when the incident happened. This has certainly led to shock/trauma to some of the passengers who either witnessed the incident or where around when it happened, but it is unclear how many and to what degree of impact.

5.5.9 Train Delays and Cancellations

Prevention of incidents can avoid disruption of services leading to delays and cancellation of trains. This is linked with the ability of PSDs to prevent incidents from happening, thereby reducing the disruption rate that leads to such cancellation and delays.

The Service disruption estimated in Section 5.3.4 already includes the consequences due to delays and cancellations. Therefore, there is no need to estimate it as a separate entity; recognition of it would suffice.

5.5.10 Customer Satisfaction

Customers are at the heart of rail operation and their satisfaction with the services provided for them matters. Transport Focus (IRO, 2019) conducted a passenger survey as they regularly do to determine customer satisfaction with the services provided on the British mainline network. The results from the survey show a decline in customer satisfaction during a period (autumn 2018) that experienced what they termed *timetable* *chaos*, *lamentable strikes* and *worsening punctuality* due to on-going network-wide improvement works. During the 10-week survey period, 27,000 passengers were asked about their latest rail journey and 21% of those (approximately one in five) were not satisfied. This alarming issue could hint to the industry that when services are regularly disrupted, passengers' trust in the industry is being lost.

The implication of low customer satisfaction is that, customers may start to lose confidence in the system and become unhappy with the service, hence considering the use of alternative transportation modes to get to their destinations. This means fewer passengers for the rail industry and less revenue from fares – not good for all.

Because PSDs prevent incidents and subsequently avoid disruption, they can then ultimately increase customer satisfaction and indirectly attract more customers to the rail industry. However, this is considered insignificant when compared to other benefits discussed in various sections of this thesis, such as safety, etc.

5.5.11 Disutility of Travel

Disutility of travel refers to discomfort or an unfavourable experience associated with the travel process. Disutility of travel is therefore inversely proportional to customer satisfaction and can be influenced by three PSD-related factors, namely *passenger behaviour*, *passenger shock/trauma* and *disruption*. Good passenger behaviour would decrease the disutility of travel, whereas shock/trauma and disruption would increase it (see Figure 5.2). Overall, the effect of PSDs in relation to the utility of travel is minimal and is considered insignificant because there are many more non-PSD-related factors affecting the disutility of travel such as a change in the timetable, crowded trains (Thompson and Sharma-Brymer, 2011), etc.

5.5.12 Service Reliability

With frequent disruption of service, customers would tend to rely less on the service being provided. If one incident is prevented, the reliability would increase even though it may not be apparent by how much.

Other PSD-related factors affecting reliability include *platform waiting time* and *capacity* alike. When passengers wait more than necessary on platforms, there is a likelihood that they will become less reliant on the train service. Likewise, an increase in capacity (more trains, shorter headways) would certainly increase reliability and vice versa.

5.5.13 Optional PSD Functions

PSDs can be installed with only the primary function of separating the platform from the tunnel. However, other value-added functions can come along with the PSDs at an added cost (Abdurrahman *et al.*, 2018). These include:

1. Gap closing
2. LED Lights
3. Heating/Cooling
4. Media

Gap Closing

Gap closing is an MGF (mechanical gap filler) function that sometimes comes with PSDs for the purpose of bridging the horizontal gap between the train and the platform edge. Wide gaps at the PTI, whether vertical or horizontal, are not recommended (Rodríguez *et al.*, 2016) and can pose a danger to passengers, especially children and the elderly who could find crossing the gap difficult.

The function can ease passenger exchange in and out of the train, eliminate tripping risks and shorten the time it takes to cross the PTI, thereby reducing boarding and alighting time. There are different types of gap-closer, e.g., gap-closers that are retracted when there is no train, sliding out when a train stops to bridge the gap. It slides back before train departure to avoid interfering with train movement.

LED Lights

LED lights are another element that are incorporated into the modern PSD designs to aid visibility, especially during dark hours, even though in most underground stations it is always dark, unless the platforms are well lit.

Locating LED lights at the base of the doors can help improve PTI safety, particularly for passengers with visibility challenges. It provides clarity of stepping positions on the PTI for smooth crossing on and off the train.

Heating/Cooling

A heating and/or cooling function is another function that comes with the PSDs according to the specification given in the terms of the contract. The aim is to provide a set of devices to be used for environmental conditioning, i.e., heating the platforms during the cold seasons and cooling during hot seasons, where appropriate. By so doing, the requirements for independent platform heating/cooling devices would be reduced to a minimum.

The incorporated devices usually come at an additional insignificant cost in comparison with the main procurement cost of the whole PSD system; it is, however, worth acknowledging.

Media

The media function is another value-added feature that comes with PSDs to add to their functionality. Most full-height PSDs come with an option of display screens used for various purposes including a *passenger information display* for minutes left for the next train to arrive/depart, train schedule, doors locked out of service, etc.

The media function can be divided into three categories, namely:

1. Passenger information screen
2. Advert potential

3. Announcement potential

The *passenger information screen* is usually located just above the doors for display of digital content regarding the passenger journey.

Advert potential is provided through advertisement spaces on the fixed door panels which could be used to display adverts either using printed posters on the screens or using an in-built Liquid Crystal Display (LCD) to project the adverts electronically. Advertisements are generally a source for revenue generation and are featured in most rail systems.

Announcement potential is derived from the use of in-built sound devices that can be used to communicate to passengers any information relevant to their travel. This could be a change in schedule, delayed trains, change of platforms for departing trains, security-related information, etc. This eliminates the need to provide additional sound devices on the platform. Again, this is not comparably significant.

5.5.14 Recap of Immaterial Factors

The factors discussed in the sections above are deemed insignificant, and they are not incorporated among the factors that would likely influence a decision, their values (estimated in Appendix D) are judged to be negligible in comparison to the significant factors, for example energy consumption, incidents, etc.

For the sake of clarity, both insignificant factors and neutral factors can be incorporated into the model when a user feels the need to include some or many of them for any reason. This enables having a bespoke model for a specific system with a more in-depth analysis.

5.6 Summary

The method presented in Chapter 3 has been put into action in this Chapter, enabling the development of an SD model showing various factors of the railway that are affected by the deployment of PSDs on platforms. The Chapter discusses one of the most important aspects of this thesis, namely mathematical model development. Relationships were developed for the factors under consideration and quantification processes were established to enable a comprehensive appraisal of the PSDs. The factors that were not quantified were also discussed, giving justification for each.

The 41 equations created are used in the development of the generic executable model that paves the way for statistical analysis. The model, results and analysis are presented in the next Chapter.

Chapter 6

Model Results and Analysis

6.1 Preamble

This Chapter presents the generic model developed using the mathematical equations discussed in Chapter 5. The Chapter also features an economic analysis of PSD deployment using a set of normalised real data referred to as the hypothetical station characteristics; results were obtained and interpreted to advise the decision-making process in the case of PSDs.

6.2 Generic Model Development

In addition to the SD model, an executable model was also developed which captures the identified PSD issues and arithmetically calculates the monetary value of each; these were then combined to form the overall CBA regarding the decision to deploy PSDs on a certain platform, station or an entire railway network. This model is capable of customisation to suit different railway networks and varying requirements in order to effectively assess the viability of PSD deployment. The model structure and contents would potentially be useful when developing a business case for retrofitting of PSDs on any existing network, or for new designs. In the model, cost components and benefit components are clearly articulated and estimated, drawing a clear picture as to what PSD deployment would lead to. This is all based on the user input of basic local data that would be required for running the model.

6.2.1 The Model Workbook

The main model was developed in the Microsoft (MS) Excel application which has a long-term reputation for model development and data processing. Several Excel spreadsheets were created within the same workbook to serve respective purposes, namely:

1. About the Model
2. Information Dashboard
3. Glossary of terms
4. Input
5. Computation
6. Summary of results
7. Conclusion sheet

About the Model

This is the first sheet and it contains a description of what the model is, why it was developed and the functions it is intended to serve. It captures information about the model being part of a PhD study and that details are contained in this thesis. Also contained in this sheet is information about the author, supervisors, institution and sponsor of the research. A screenshot of this sheet is shown in Appendix F.

Information Dashboard

The *Information dashboard* contains information about the model layout, similar to what is provided in this Section of the thesis (Section 6.2). Meanwhile, it describes, in a concise way, the kind of data and/or information contained in each sheet of the model so that users can refer to it when needed for further information (see Figures F.2 and F.3 in Appendix F).

The dashboard is structured in a tabular form displaying the key to all sheets. This includes the serial arrangement of the sheets, details of what each sheet contains, and further remarks to help users become familiar with the whole workbook for practical use.

There is an additional panel on the dashboard containing clear instructions to users of the model on how to make the best use of it. Here, it is clearly stated that, as designed, the model works on the basis of one platform. However, it could be used for prediction for a set of platforms at a particular station or more widely on a number of or all platforms on the railway network in question. The model is capable of dealing with these varying demands based on averaging the data supplied over the number of platforms inserted. The panel also features explanations of the default values and the currency information panel.

Glossary of Terms

This is a sheet dedicated to definition of the terms, units and abbreviations either directly used in the model or useful for understanding various factors in the model. The terms are listed in alphabetical order in one column followed by another column (labelled *meaning*) which explains what each term means and another column for remarks (additional information that is not captured in the *meaning* column). Beside this, is a Section containing definitions of input parameters.

Input

The *Input* sheet is structured in such a way that it contains a set of all the variables that could be used in the model. These variables are grouped into similar sets of information, namely: platform incidents, station particulars, staff information, energy information, PSD information and operational/others. There are a number of factors under each group which would require an input from the user in the *Your Input* column. For guidance, a column of units is provided to help users understand a bit more clearly what each factor is.

The *Input* sheet is where the main user interface takes place (see Appendix B). It contains various sets of information from various railway networks across the globe which were merged to form the unified values for each factor that could be used as a benchmark or default value for running the model. This information was acquired from the respective metro operators or reliably published data, and hence they are real industry data, not assumptions. The data used to form the benchmark values are hidden in the model to preserve confidentiality and because they are not directly needed by the user. The data used are from the following rail networks:

1. Seoul Metro
2. Singapore Mass Rapid Transit (MRT)
3. Hong Kong Mass Transit Railway (MTR)
4. London Underground
5. Crossrail, UK

These benchmark values, labelled *default values* in the model, serve as an automatic or default input in positions where the user does not insert their own network-specific values. This could be due to a number of reasons including, for example, as a result of the user not knowing these values, or the data required not being available on the user's database, or the user testing for a brand new network that is not yet in operation, hence there is no real data, etc.

Available on this sheet is the option for indicating the number of platforms the user wishes to evaluate. This is important in generating a more accurate CBA at the end of the execution to let the user know precisely the financial consequences for all the platforms under consideration, or network-wise as the case may be. This enables the generation of the total benefits and the total disbenefits as a multiple of the number of platforms on the network being evaluated. With that in mind, the user inputs then become an average of the data taken for all platforms, following the units indicated against each factor, which are usually per platform.

Additional (blank) rows are provided for the user to include any other factors, e.g., non-valued issues from the list of identified factors on the SD model for when they justify their significance in a particular case.

Still on the *Input* sheet, the model shows specific values against each factor that the model uses in its calculations. These values would either be the user input values or (automatically, in the absence of user input values) the default values. Alongside, there is another column that indicates with a tick sign (√) whether the value used is the default. All in all, this information is used in generating a percentage of user contribution used by the model to generate the output shown on the *Conclusion* sheet.

A currency conversion panel positioned at the right side of the *Input* sheet provides an easier way of converting from one currency to that on which the model is built (pounds sterling (GBP), £). The currency conversion panel enables the user to write down the name of the currency they are using, and the conversion rate to GBP. That is all the user will have to do in terms of currency conversion. The model then automatically changes all currency-related figures into the equivalent of the currency the user has input. The user is then able to make their further inputs in the local currency.

Computation

All the mathematical equations developed (see Chapter 5, Section 5.3) are used in the *computation* sheet to generate values for each factor under consideration. Units are provided for each parameter beside which the calculated value is displayed for the conditions with and without PSDs.

The sheet is there to display the calculated values. The user is not able to adjust the contents of the sheet since it is just for displaying the values against each of the grouped variables. For example, the value for the total safety record is displayed by calculating all safety-related issues and combining those together. These include the total platform incident record and the record of workforce shock/trauma.

The layout of this sheet makes it easier for one to clearly see the current condition, i.e., without PSDs, and the projected condition with PSDs, so that it is clear to see the individual differences in the two scenarios for each parameter, whether a gain or loss.

The *Net Present Value* (NPV) is indicated at the bottom of the page as the result of all benefits and disbenefits being considered together. This NPV can either be positive or negative depending on the data used to run the model, negative being an overall loss and positive being an overall benefit.

Summary of Results

The *Summary of Results* sheet contains the wrap-up from the *computation* sheet, showing the main values of each grouped parameter set. The page provides two sections displaying the main results for an average platform and for all platforms. These sections each clearly show the impact in the form of a present value alongside an indication of whether a particular factor turns out to be of benefit to the entire system or the obverse. A screenshot of this sheet is shown in Figure F.4 in Appendix F.

Having only used the main values here, they are used to generate the graphs capturing the main indicators for installing PSDs on a particular platform or over an entire network. These graphs are shown on the *conclusion* sheet of the model.

Conclusion Sheet

The *conclusion* sheet is where the summary of the whole model is displayed. In other words, it is the output page of the model. The key results shown on the sheet include:

1. Overall benefit
2. Overall cost
3. Benefit-cost ratio
4. Net present value

Just below these, there is a recommendation panel which provides concluding remarks/advice based on the output of the calculated values. These key results are presented for the *average platform* scenario as well as for the *all platforms* scenario.

There are basically five recommendation criteria used; these are solely based on the calculated Benefit-Cost Ratio (BCR), and are presented later in Chapter 6, Figure 6.3.

Also on this sheet is a panel indicating the percentage of default values used, and a percentage of user contribution based on the data entered. These percentages are calculated using the number of inputs made by the user in comparison with the number of default values automatically used by the model. For instance, if all the variables are keyed in by the user, then the percentage of user contribution would be 100%. But in an instance where some of the variables are not entered by the user and the default values are used, the percentage of those would be discounted (see Figure 6.2).

There are two graphs on this sheet, as mentioned in Section 6.2.1. One is for an average platform (or the particular platform being tested) and the other is for all platforms (on the line/network). These graphs depict the benefits or disbenefits resulting from the deployment of PSDs specific to user data (see Figure F.5 in Appendix F).

6.2.2 Validation and Modification

Upon completion of the model, it was rolled out to industry contacts seeking their feedback on whether they think the model would be useful for the industry, whether the values used (as default) and the concepts are sensible, and any other comments that they may have on the model. The feedback received was then reflected in the model, thereby producing a final version (feedback details in Section 6.3.5).

6.3 Features of the Model

The generic model was developed in the Microsoft Excel environment in the form of multiple spreadsheets each serving a purpose. There are a total of seven sheets in the workbook, all of which are described in detail in Section 6.2.1.

6.3.1 How it Works

The model takes input from the *Your Input* column if data are provided. If not, the model takes its data from the default values, but it will then report this as a percentage of user contribution. All arithmetic calculations are carried out in pounds sterling as the primary currency. However, there is a currency conversion panel to use for conversion from other currencies, available in the entry space (the input sheet).

The data are then processed in the *computation* sheet of the model. The computations are carried out for every single factor but then grouped into main categories and displayed in the *summary of results* sheet. This result is used to produce the waterfall charts for a single platform and a combined chart for all platforms, alongside other outputs as outlined in Section 6.3.4.

The equations developed in Section 5.3 are all integrated in the model and used for carrying out the computations in the background.

6.3.2 Incorporating Local Factors

Local factors are the specific input data that would be obtained from the rail network being tested for the deployment of PSDs. These can be keyed into the model in the column titled *Your Input*. There are numerous factors requiring data input for the model to process and provide a result. Figure 6.1 is a screenshot from the model showing these factors. The Figure also reveals a checklist of the things to lookout for when considering installing PSDs.

6.3.3 Benchmark Values

The benchmark values, referred to as the *default values* in the model, are derived from a combination of various data from reputable rail networks, namely the Seoul Metro, LUL, Singapore MRT, Hong Kong MTR and Crossrail UK.

Please key in the data in '*Your Input*' column

ePSD Model Please indicate **number of platforms**: **2**

S/N	Parameter	Unit	Your Input
	Platform Incidents		
1	Avg. platform trespass	FWI/platform-yr	
2	Avg. platform accidental falls	FWI/platform-yr	
3	Avg. platform suicides	FWI/platform-yr	
4	Avg. platform mantrap incidents	FWI/platform-yr	
	Station Particulars		
5	Number of platform staff	staff/platform	
6	Avg. number of platforms per station	platform/stn	
7	Avg. station dwell time	sec	
8	Anticipated PSDs' effect on dwell time	sec	
9	Avg. daily station operation hours	h/day	
10	Single journey fare	£/journey	
11	Avg. journey length on the network	min/journey	
12	No. of train door sets per platform	doors/platform	
13	Frequency of train at station (capacity)	tph	
14	Number of train stops along the line	platform	
15	Avg. platform length	m/platform	
	Staff Information		
16	Hourly overtime pay rate of train driver	£/h	
17	Weekly working hours of train driver	h/week	
18	Number of DCR staff required	staff	
19	Annual Salary of DCR staff	£/yr	
20	Annual PSD/DCR Staff training cost	£/yr	
21	Workforce time lost due to incidents	weeks/FWI	
	Energy Information		
22	Avg. station HVAC energy consumption	kWh/yr	
23	Unit cost of energy	£/kWh	
24	Daily standing charge for station energy	£/day	
25	Anticipated HVAC savings with PSDs	%	
26	Auxiliary train power	kW	
	Operational/Others		
27	Avg. service disruption rate	min/FWI	
28	Unit cost of delay minute	£/min	
29	Rate of lost customer hours	h/FWI	
30	Rate of workforce shock/trauma	-	
31	Change in platform air pollution (PM_{10} etc)	$\mu g/m^3$	
32	Damage cost of pollutants	£/person-yr/µg/m3	
33	Change in ambient platform noise	dB	
34	Damage cost of noise annoyance	£/person-yr/dB	
35	Value of preventing a fatality (VPF)	£/FWI	
36	Standard discount rate	%	
37	Health discount rate	%	
38	Maximum passenger capacity per traain	p/train	
39	Average (train) riding occupancy	%	
	PSD Information		
40	PSDs purchase & installation cost	£/m	
41	PSDs maintenance cost per linear meter	£/m-yr	
42	Cost of PSDs half-life overhaul	£/m	
43	Extra function cost	£/platform	
44	PSDs Power consumption per door set	kW	
45	Lifetime of PSDs (also, years of analysis)	yrs	
46	Cost of taking the PSDs down at lifetime	£/m	
47	Salvage Value of the PSDs	£/m	
	Parameter 1	unit	
	Parameter 2	unit	
	Parameter 3	unit	

FIGURE 6.1: Model Parameters Requiring Input from the User (Author)

In a situation where the user has no particular information about the required input, the cell can be left blank and the default value in the model is automatically applied. This, however, reduces the confidence that any user can have of the results produced by the model with regard to their specific network. The *user contribution* information can serve as an indicator of how confident the user can be that the results apply locally. The percentage of default values used (see Figure 6.2 as an example) is also provided as part of the conclusions. The more default values used, the less confidence the user can have in the results and vice versa. For details on the default values, please refer to Section 6.2.1 under the *Input* heading.

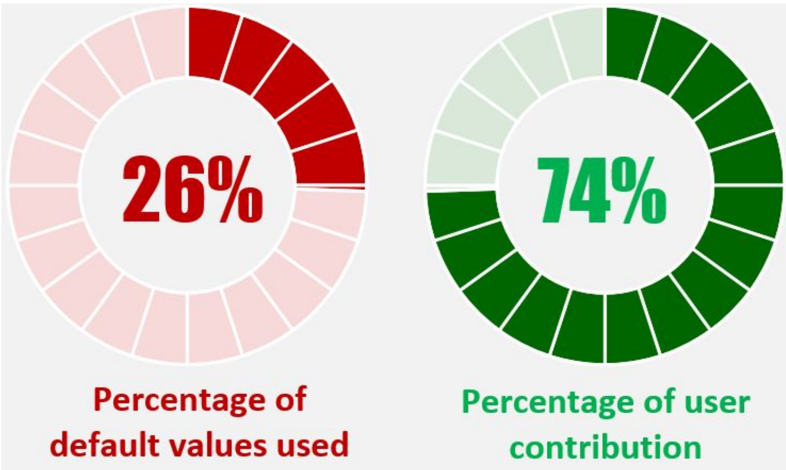


FIGURE 6.2: A Sample of the User Contribution Calculated as a Percentage of the Input Data which Come from Real Local Values (Author)

In addition, there are parameters against which the use of the default value is not recommended because even a small variation in them can lead to a significant impact on the final results. These include all safety factors (accidental fall, trespass, suicide and passenger entrapment), energy consumption, PSDs' effect on dwell time, cost of having the PSDs, and the Value of Statistical Life (VSL). Details are given in Section 6.4.3.

6.3.4 Output Interpretation

In total, there are eight key results forming the conclusion based on the input data. These are presented in the *Conclusion* sheet of the model. The results are in two forms

- one for an average (or the particular) platform being tested, and another for all platforms on the line (or network, depending on the input). The key results are:

1. Overall Benefit
2. Overall Cost
3. Benefit-Cost Ratio (BCR)
4. Net Present Value (NPV)
5. Percentage of default values used
6. Percentage of user contribution
7. Quantified PSD factors (waterfall)
8. Recommendation

Overall Benefit refers to the financial equivalent of the total gain that could be derived from the deployment of PSDs, whereas *Overall Cost* refers to the financial equivalent of the total loss and expenses arising from deployment. The ratio of the two is what gives the BCR which further governs the *recommendation* (see Figure 6.3) based on the customisable BCR criteria for economic appraisals.

A positive NPV indicates that the investment is worthwhile and would yield an overall gain (using discounted values) equal to the amount carried by the NPV. A negative NPV means the amount invested would not be recovered during the lifetime of the PSDs, leading to a net loss equal to the amount carried by the NPV. This ensures that decision makers are informed of the possible financial yields for that appraisal.

The percentage of default values used and the user contribution are discussed under *Benchmark Values* in Section 6.3.3 and captured in Figure 6.2. The *quantified PSD factors* indicates the financial weights carried by the major categories of factors as sampled in Figure 6.5.

The largest benefit in this particular scenario is in the form of safety, which is mainly a benefit to society and does not usually return money to the companies investing in

You Can Customise These Criteria		
Lower BCR	**Higher BCR**	**Recommendation Criteria**
1.50	>1.50	There is a strong case for full-height PSDs under the current circumstances. Hence, full-height PSDs are strongly recommended.
1.00	1.50	Full-height PSDs may have a marginal benefit. It is recommended that you do some detailed evaluation. However, Half-height PSDs would be most suitable under the current circumstances.
0.75	1.00	There is a weak case for full-height PSDs, but a marginal benefit may be achieved with half-height PSDs. It is recommended that you do some detailed evaluation on half-height PSDs.
0.00	0.75	It is uneconomical to consider PSDs under the current circumstances.
Else		You might have made some mistakes in your input. Please verify and try again.

FIGURE 6.3: Customisable Recommendation Criteria Based on BCR (Author)

these doors. This depends on the incidents and their causes. Most of the time, safety incidents are assessed to identify the cause(s). Suicide incidents in particular do not normally attract compensation, but for incidents for which the infrastructure/facility is to blame, there would be an issue of compensation using the VPF/VSL for fatalities and an appropriate share for injuries, depending on the country's regulation and the nature of the incidents.

6.3.5 Verification and Validation

All through the process, right from the concept development through to producing an executable model, there have been consistency checks with relevant stakeholders that are involved in the design, decision-making or supply of PSDs. A series of verification and validation exercises was carried out as detailed in the following sections.

Verification of Causality

At the initial stage, the causality developed was taken through a verification process using the *causes tree* and *uses tree* diagramming techniques explained in sections 5.2.2 and 5.2.3 respectively. Each parameter from the causal structure was viewed in their respective *causes* and *uses* trees to make sure that its causes and effects were accurately mapped in the CLD. This was later checked by railway consultants, academics and a PSD supplier who has experience in the industry, particularly on the production side of things.

Validation of Method and Equations

The mathematical equations developed in this thesis were validated through industry contacts working with various stakeholders in the UK, Singapore and Hong Kong. These stakeholders work in the capacity of PSD supply, railway project consulting, railway operation and academic research and education. A series of meetings was held, during which checks were carried out on the identified issues, the relationships including equations, particularly for factors requiring specialised attention such as safety, energy, etc., and the overall modelling.

Model Validation

To ensure the industry was carried along to the end, the model was rolled out for validation to industry contacts. The aim was to get feedback on using the model and how, in their experience, the model could be improved to better support both designers and decision makers. Five railway professionals were contacted for the validation and testing; they work in the following roles:

1. Consultant Engineers $\times$ 2
2. Railway Operators $\times$ 2
3. PSD Supplier $\times$ 1

Of these, there were responses from two experts, a consultant engineer and a railway operator. These experts, after engaging with the model, provided feedback which is summarised according to the experts' individual comments.

The feedback received from Consultant Engineer 1 is as follows:

1. Define the variables, particularly those on the input page, so that users would exactly know what is required of them as an input.

2. Check the calculation of *capacity* and that of the *fare revenue due to service disruption* to make sure there is no double counting.

3. Recommended as a next step to have a test case for the model on a real PSD case scenario to discover its full contribution to the stakeholders.

The first piece of feedback was positively taken and an additional Section was created in the *glossary of terms* sheet, containing a short description of each of the variables appearing on the input list.

Regarding the second point, an explanation was supplied that the two factors were not similar, hence there was no double counting as feared. The effect on capacity would be inscribed in the schedule thereby restricting, in a way, the headway window, and therefore the number of trains that can be run per unit time. The fare lost due to service disruption is a different scenario associated with the potential occurrence or prevention of incidents, which yields a temporary effect on the passenger-carrying capacity.

The third point was well received and happens to be in line with the author's recommendation for taking this work further (see Section 7.6).

Consultant Engineer 1 also made this general comment upon completion of the model assessment:

> *'This is a very good model. It will be useful for the industry, not just for decision makers and designers but also for those preparing a bidding document on a case for PSDs. It provides a reference list of factors that may not otherwise be thought of while deciding to have PSDs on either new or existing lines.'*

There were three main feedback from Railway Operator 1 as summarised below.

Feedback 1:

'Anticipated PSDs' effect on dwell time - 5 sec may be on the high side, the latest signalling system safety calculation time should be able to reduce the delay to less than 3 secs. This could alleviate the reduction in train frequency in your model (28 to 27) which is detrimental to service and train capital investment.'

After receiving this feedback, the model was run with different dwell time delays. It was clear that the change in dwell time has a direct impact on train frequency. Therefore, the model was designed to allow user input for (anticipated) dwell time delay to enable calculation of the corresponding impact on the train frequency. The dwell time delay used as default (5 seconds) was as a result of average of multiple data obtained from various rail systems.

Feedback 2:

'Value of service disruption - The percentage change in capacity. I am not sure about your rationale in the calculation and the impact on value of service disruption.'

This feedback suggests the need to clarify the essence of including service disruption in the analysis. The author has responded to this by saying; 'I estimated the service disruption impact looking at the delay minutes presumably generated by each incident. Prevention of such incidents by PSDs leads to avoidance of delay minutes. The value of service disruption is therefore derived from the alleviated delay minutes.'

Feedback 3:

'Value of increased platform space - Not sure how you can factor in your model, but PSD can create more space in the platform for waiting passengers which is very valuable for near-capacity operation.'

This is a good suggestion which, as pointed out by the reviewer, could be valuable for stations approaching their passenger capacity limit. As regards to this, the author has developed equations that can be used to estimate the increase in platform capacity resulting from the released space at PTI which can accommodate more passengers. This is discussed in Section 5.3.7.

6.4 Economic Analysis

In order to provide advice to designers and decision makers, it is desirable to have a common unit base with which a comparison can be made for various aspects of the railways and how they would all be affected. To this effect, this research has chosen the common unit of money.

All effects were estimated in terms of their existing common descriptors and then, if needed, converted into money (either gained or lost) using established methodologies which enabled a conclusion and advice on whether to deploy PSDs. These are generated as elaborated in Section 6.4.2.

6.4.1 Discount Rates

For the purpose of this analysis, standard discount rates from four countries, namely Singapore, Hong Kong, Korea and the UK were considered to form an average of 2.68%. This was used for all evaluations except for safety analysis for which a health discount rate of 1.50% was used in accordance with the recommendation of *The Green Book*, a UK government document for guidance on appraisal and evaluation (HM Treasury, 2018). However, the model produced by the author allows one to enter different rates appropriate to their local circumstances.

6.4.2 Cost-Benefit Analysis

The data used to generate results are based on a hypothetical platform, belonging to a hypothetical station which has the characteristics given in Appendix B. These values are what are presented in the model as *default values*. The analysis presented in this Section comes from the application of these default values.

ePSD Model

These **calculated factors** are based on the data entered into thet, and are for an **average platform**.

Bottom ↓

S/N	Factors	Without PSDs	With PSDs	Difference	Present Value
	Total platform incident record	0.1308	0.0009	0.1298	
	Workforce shock/trauma	0.0007	0.0000	0.0006	
	Total safety record	0.1314	0.0009	0.1305	
1	**Value of total safety record**	**255,727**	**1,829**	**253,899**	**6,874,456**
	Lost customer hours (LCH)	1,596	11	1,585	
2	**Value of fare revenue for lost customer hours**	**4,458**	**32**	**4,426**	**99,764**
	Dwell time	33	38	5	
	Delay minutes due to disruptions	12.42	0.09	12.33	
3	**Value of service disruption**	**3,106**	**22**	**3,083**	**69,499**
	Traffic Headway	130	135	(5)	
	Train frequency (Line capacity)	28	27	7,355	
	Percentage change in capacity	0.00%	3.71%	(3.71%)	
4	**Value of change in capacity**	**0.00**	**246,926**	**(246,926)**	**(5,565,858)**
	Change in train energy consumption	0.00	458	458	
	Cost of change in train energy consumption	0.00	55	55	
	HVAC energy per platform	4,882,810	3,119,627	1,763,183	
	Cost of platform HVAC energy consumption	585,474	374,094	**211,380**	
	Door Activations	0.00	11,113,637	(11,113,637)	
	PSD Function Energy	0.00	164,591	**(164,591)**	
	Cost of PSD Function Energy	0.00	19,732	**(19,732)**	
5	**Value of Overall Energy**	**585,474**	**393,881**	**191,593**	**4,318,623**
6	**Value of air quality improvement**	**0.00**	**(1,125)**	**1,125**	**30,470**
7	**Value of ambient platform noise**	**0.00**	**(35)**	**35**	**936**
	Lost workforce hours	27.46	0.20	27.26	
	Cost of replacement Driver	733	5	728	
	Cost of DCR Staff	0.00	24,278	(24,278)	
	Annual PSD/DCR Staff training cost	0.00			
8	**Value of Staffing**	**733**	**24,283**	**(23,550)**	**(530,829)**
9	**Net cost of PSDs installation**	**0.00**	**3,370,299**	**(3,370,299)**	**(3,370,299)**
10	**Net cost of PSDs maintenance**	**0.00**	**64,169**	**(64,169)**	**(1,446,404)**
11	**Net cost of PSDs half-life overhaul**	**0.00**	**1,193,492**	**(1,193,492)**	**(751,819)**
12	**Net cost of taking the PSDs down at lifetime**	**0.00**	**229,174**	**(229,174)**	**(90,940)**
13	**Net salvage value of PSDs**	**0.00**	**(229,174)**	**229,174**	**90,940**
	Parameter 1				
	Parameter 2				
	Parameter 3				
				Net Present Value → £	**(271,461)**

Top ↑

FIGURE 6.4: Key Results Obtained Using All Default Values (Author)

Using the mathematical models presented in Section 5.3 in the executable model, the results generated are as shown in Figure 6.4. There are 13 key results from this analysis. Seven of them yielded positive results, indicating benefits upon deploying PSDs. The other six negative results are telling us that deploying PSDs would have a negative effect on these parameters namely: capacity, staffing, installation cost, maintenance, half-life overhaul and decommissioning. The latter four of these are obvious because they are the direct cost components of installing and using the PSDs.

Capacity turned out to be negative because of the PSDs' effect on dwell time, adding a total of 5 seconds to each dwelling activity in this particular case (see Appendix B). This extension would not be counted as part of the planned delay because it is incurred as a result of having the PSDs, without which there would not be any. Therefore, they accumulate to affect the capacity of the line as long as the plan is to maintain the existing headway. It is therefore strongly recommended that PSD systems are designed to sync with train doors with as low a latency as possible to reduce (or if possible, eliminate) the additional dwelling time, therefore mitigating the impact on capacity.

Staffing would be another negative factor because of the need to dedicate staff in either the OCC or the DCR, if any. This is in addition to the platform staff that may be required depending on the practice, specific system requirements and/or reliability issues of the PSDs.

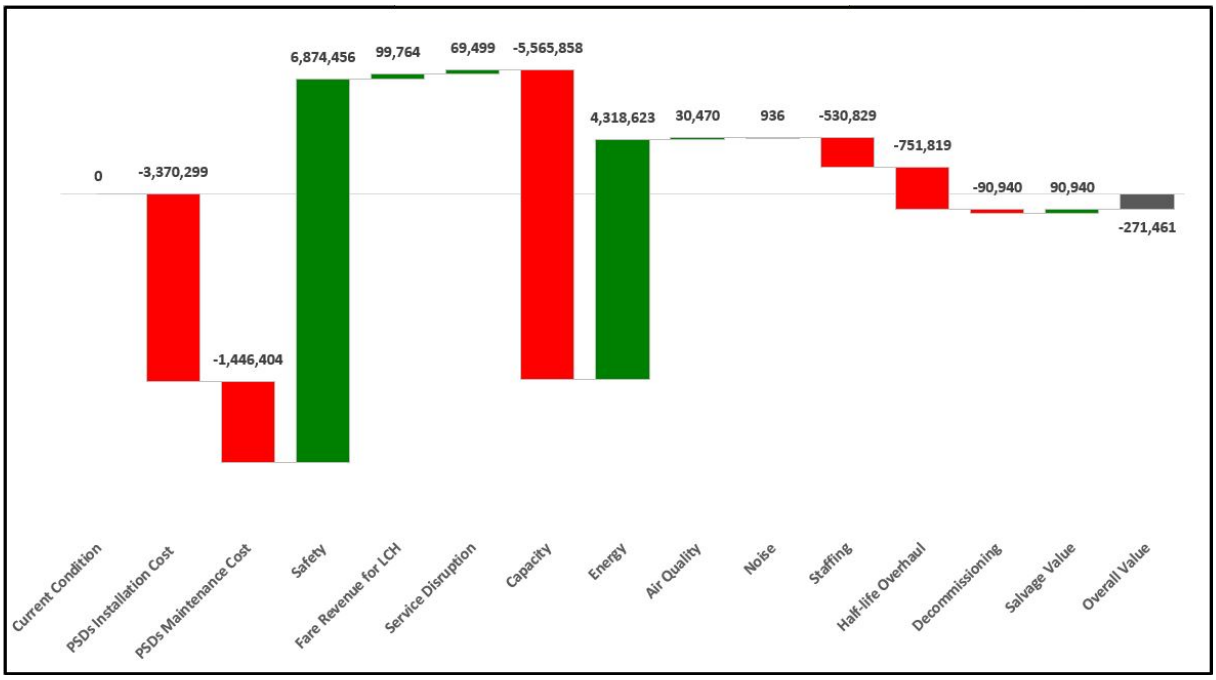


FIGURE 6.5: Quantified PSD Factors on the Basis of One Platform Over 35 Years [in £] (Author)

The seven positive results as indicated by the green bars in Figure 6.5 are the benefits that would be derived from deployment of the doors. Of these, *safety* has the greatest benefit (£6,874,456), coming from the doors' function of preventing platform incidents which accrue a very high amount depending on the VSL or VPF which in this case is the RSSB's value of £1,946,000 per fatality (RSSB, 2018b). A fraction of this would be allocated to weighted injuries. See table 6.1 for the FWI weightings used, as adapted from the UK RSSB (2018a).

TABLE 6.1: FWI Weightings by Degree of Injury (RSSB, 2018a)

Injury Degree	**Weighting**	**Number of Injuries Equivalent to One Fatality**
Fatality	1.0	1
Major Injury	0.1	10
Class 1 Minor Injury	0.005	200
Class 2 Minor Injury	0.001	1,000
Class 1 Shock/Trauma	0.005	200
Class 2 Shock/Trauma	0.001	1,000

The next significant benefit is that of *energy*, amounting to £4,318,623 over the lifetime of the PSDs. This includes all energy savings in the form of HVAC and excess train energy consumption, less the PSDs' function energy. Other benefits include savings in the LCH, service disruption, air quality improvement, noise suppression and the salvage value of the PSD components during decommissioning.

Detail of the Case Study

The benefit and cost factors calculated were in accordance with the mathematical equations developed and presented in Section 5.3. An example of the calculation is worked out here for *fare revenue for LCH* factor for the purpose of illustration. The following equation was used.

$$V_{fr} = \frac{60}{J}\left(h_{lc} \times f_0\right) \tag{6.1}$$

Where:

V_{fr} = value of fare revenue (£/yr)

$\bar{J}$ = average journey length (min/journey)

h_{lc} = lost customer hours (hr/yr)

f_0 = single journey fare (£/journey)

Now, the numerical value of the variables involved are taken from the normalised data obtained from the prominent rail networks. The data for this particular set of variables are shown in Table 6.2.

TABLE 6.2: Data for Fare Revenue Calculation (Author)

S/N	Factor	Data
1	$\bar{J}$	39.96 minutes
2	h_{lc}	12,209 hr/FWI * 0.1289 FWI/yr
3	f_0	£1.86

Therefore, the value of fare revenue for LCH is;

$$V_{fr} = \frac{60}{39.96}\Big(12,209 \times 0.13 \times 1.86\Big) = \pounds\, 4,426 \; per\ year \tag{6.2}$$

This amount is then obtained for each year of the PSDs lifetime and converted to the statistical equivalent of its present value. The procedure is carried out for all quantified factors.

Benefit-Cost Ratio

As shown in Figure 6.5, the cost components are those indicated to have a negative impact (the items shown red in the chart), for which respective financial equivalents were obtained. Likewise, the benefits derived as a result of deploying PSDs are shown as green components in the Figure. Red elements are subtracted from the value and green elements added. Hence, the overall cost and overall benefit of deploying PSDs on the hypothetical platform are the sum of each component. These are shown in Figure 6.6.

The BCR for the default values is obtained by taking an arithmetic quotient of benefits and costs:

$$BCR = \frac{benefits}{costs} \tag{6.3}$$

$$= \frac{11,484,688}{11,756,148} = 0.98$$

Therefore, the BCR of deploying PSDs on the hypothetical platform is 0.98. This indicates that the benefit is just less than the disbenefits and would therefore not cover the cost of having the PSDs. However, as the BCR is very close to 1.00, it is an indication that the difference between the benefits and the costs is not significant and that, therefore, a sensitivity analysis should be undertaken. It is worth noting that the principal benefit is safety (see Figure 6.5) which is dependent on the value of life / value of a prevented fatality used in the calculation (the VPF). Therefore, a small rise in the VPF would make it justifiable to install a PSD. It would also make a stronger case if the Pareto principle were to be applied (see Section 6.5).

Consequently, as it is now, the final conclusion is that in the default model, PSDs would have an overall marginal disbenefit over their lifetime. Hence, when the model is run, the recommendation (see Figure 6.6) is that because the BCR is close to 1.00, it would probably be justifiable to consider half-height PSDs (which are cheaper) and can therefore be most suitable. However, there is a need for detailed analysis to capture their specific effects as those would vary from those of full-height PSDs, e.g., in the impact on energy consumption, air quality, etc.

That being said, various companies and organisations have their varying BCR limits for economic appraisals. The BCR does not necessarily have to be 1.00 or above for projects to get approval, especially for safety-related projects. In which case, the recommendation criteria (Figure 6.3) used in the model would have to be customised to

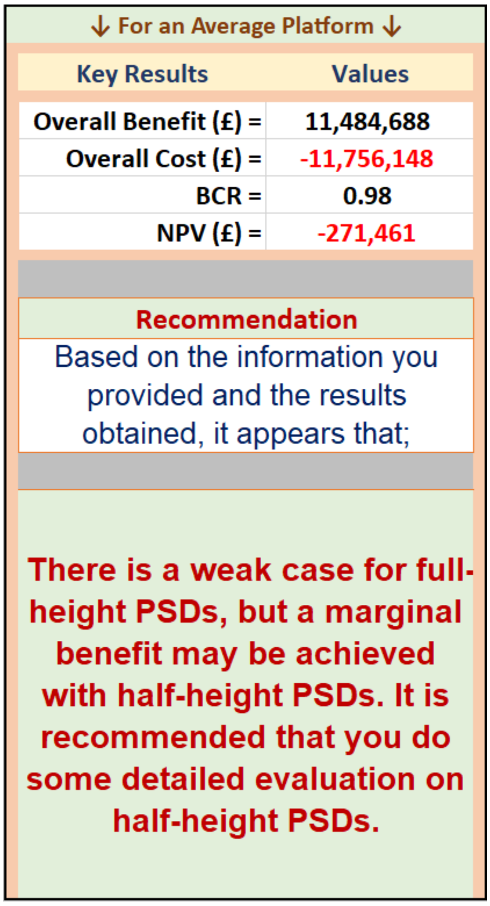


FIGURE 6.6: Cost-Benefit Analysis Results for a 35-Year Period (Author)

suit the investment requirements of that particular organisation.

Some projects may not be approved because of the limited funds that the company have available. As such, there may be PSD cases where the investment/BCR requirements are met, but due to limited funding, the project would not be signed off. Another influential factor is safety regulation which may necessitate the execution of all safety-related projects having a BCR of 1.00 or above. This has to be considered where the estimated safety benefit meets the regulation requirements.

Net Present Value

NPV is obtained by taking the present value of the overall costs away from the present value of the overall benefits. NPV therefore provides information on whether there is an overall gain or loss in the economic evaluation.

In this analysis, the NPV for the default values was calculated for a PSD lifetime of 35 years, which resulted in a net overall loss of -£271,461. A negative NPV means that the project would yield a loss equivalent to the negative amount. Hence, it is always preferable to have a positive NPV for a project to stand a chance of being approved. However, this would come down to the company's investment policy which may be different for different projects. The NPV for PSDs is heavily dependent on the discount factor chosen, because many of the benefits accrue over the full life of the investment.

6.4.3 Sensitivity Analysis

It is not uncommon that some values of a multi-factor model are often subjective (Fülöp, 2005) and can vary significantly from one case to another. This phenomenon is termed *sensitivity*. In order to determine which of the factors are sensitive, analysis is conducted on the completed model to see the level of variation of the output when some of the factors experience a change in value. This is referred to as *sensitivity analysis* (Christopher Frey and Patil, 2002; Lenhart *et al.*, 2002).

Generally, sensitivity analysis is classified in a variety of ways, but Christopher Frey and Patil (2002) categorised them in a way that fits the purpose of this thesis, i.e. into three categories, namely mathematical, statistical and graphical.

The author has carried out the sensitivity analysis using the mathematical method, i.e. through varying the input of the variables and observing the change in the output when the model is run. Upon varying the input data, it was understood that there are factors that require bespoke values specific to the system being tested. This is because they are so sensitive that a small change in them can lead to a large variation in the final results. This then affects the decision-making advice. The highly sensitive factors discovered are:

1. Safety factors: trespass, accidental fall, suicide and mantrap.

2. Station HVAC energy consumption.

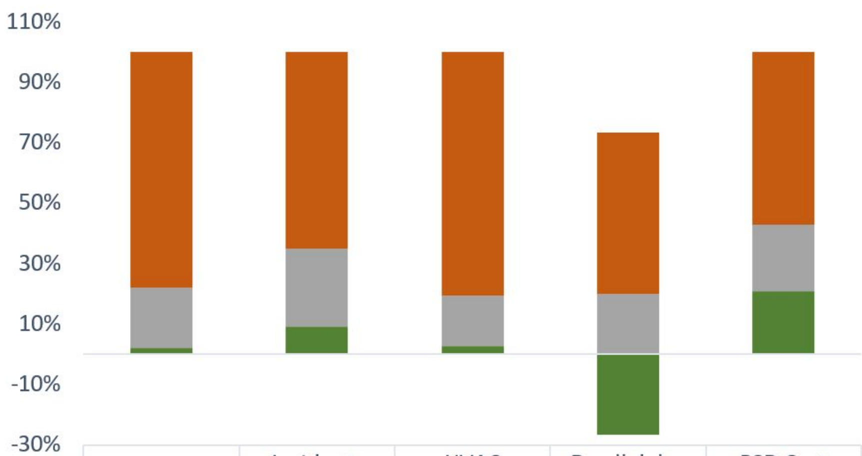
3. PSDs' effect on dwell time.

4. Cost of PSD installation.

5. VPF, often referred to as VSL.

6. Discount factor for the cash flow calculation.[1]

These parameters range in different ways on different scales. For example, the safety parameters all combined could vary from an annual zero (no platform incidents) to somewhere around a fatality every 2 years, for example. As the estimation is made for the lifetime of the PSDs, with zero incidents there would be a negligible financial benefit with regard to safety. However, a fatality every 2 years would mean about 17 fatalities over a 35-year lifetime, for example. This creates a significant change in the CBA.



	VSL (£/FWI)	Incidents (FWI/pl-yr)	HVAC (kWh/pl-yr)	Dwell delay (sec)	PSD Cost (£/m)
High	7,608,490	0.50	11,820,000	8.00	35,000
Median	1,946,000	0.20	2,443,334	3.00	13,500
Low	217,250	0.07	385,096	-4.00	12,766

FIGURE 6.7: Most Sensitive Variables in the Model (Author)

The sensitive factors were further analysed in a form of graphical sensitivity, which from its meaning complements the mathematical sensitivity analysis (Christopher Frey and Patil, 2002). This is presented in Figure 6.7 which shows a range of variations in these parameters and the effect on the final results as a percentage of the (benchmark)

[1]The discount factor has not been investigated in detail and the sensitivity to this will require further work. However, increase in discount rates will worsen the case because the cost is upfront, whereas the benefit comes year after year.

outcome. These variations were obtained from the sources used to populate the default values. Looking at it from another angle, the graphical analysis shows an exploration of the model response to specific inputs which can be helpful in knowing what factor carry a significant weight that may sway the direction of the advice given for the decision-making.

Any change in these sensitive factors could lead to a significant difference in the results. The Figure (6.7), formed using a set of data obtained from various sources (shown in Table 6.3), shows the level of variations that could occur, because different countries (or rail systems) have different values. For instance, if you use the VSL Figure that applies in the US (equivalent of £7,608,490), the implication on safety factors would be about four times that with the UK Figure (£1,946,000). These implications are summarised in Table 6.4.

TABLE 6.3: Sources of Data Used for the Sensitivities (Author)

Impact	**VSL**	**Incidents**	**HVAC**	**Dwell Delay**	**PSD Cost**
Low	India[2]	LUL[3]	Seoul Metro[4]	Hypothetical[5]	Confidential
Median	UK[6]	Seoul Metro[7]	Singapore MRT[8]	Confidential	Confidential
High	US[9]	Hypothetical	Crossrail[10]	Singapore MRT[11]	Seoul Metro[12]

Because of the sensitivity of these values, any change in them could lead to a change in the final BCR. For instance, using the 'one at a time' sensitivity measures (a technique advocated by both Hamby (1995) and Lenhart *et al.* (2002)), the model was run with VSL of the US (all other factors being the same) which led to a BCR of 2.68 in comparison to 0.98 with the UK VSL. This significant difference could change the decision of

[2] Viscusi and Masterman (2017).
[3] TfL (2014b).
[4] Sawada *et al.* (2015).
[5] Based on the research by Rodríguez *et al.* (2016).
[6] RSSB (2018b).
[7] Sawada *et al.* (2015).
[8] Thong and Cheong (2012).
[9] Kniesner and Viscusi (2019).
[10] Crossrail (2018).
[11] Personal observation on the MRT network.
[12] Sawada *et al.* (2015).

installing PSDs. In another instance, US VSL was used alongside the hypothetical 0.5 FWI (high in Figure 6.7), which changed the BCR to 9.28; a very significant change. It is therefore evident that these factors are very sensitive.

TABLE 6.4: Sensitivity Analysis as Percentage of Respective Outputs Produced from Figure 6.7 (Author)

Impact	**VSL**	**Incidents**	**HVAC**	**Dwell Delay**	**PSD Cost**
Low	One-tenth	One-third	One-sixth	One-third improvement	The same (approximately)
Median	Benchmark (median) Figures				
High	4 times	2.5 times	5 times	2.5 times	2.5 times

While the possibility of adding some factors (that are not acknowledged by this thesis) in the whole economic analysis is not negated, it is similarly possible that additional factors are also sensitive, depending on the network, geographic location, passenger behaviour, etc.

For the sake of the model, it is recommended that users should use their own data based on the actual records of the system being tested for retrofit purposes. For new systems, it is recommended to use estimates that are as accurate as possible with reference to a similar system, if any. The use of default data for these sensitive factors is therefore not recommended, hence the option is not available in the final model.

6.5 The Pareto Principle

When evaluating multiple platforms, or multiple stations, the usual way to approach this is to obtain recorded values that are usually reported as an average for all parameters over all stations/platforms. This may have a weakness because some stations may be underrated or overrated for significant variables such as the safety variables.

The *Pareto principle* states that for many phenomena, around 80% of the effects come from about 20% of the causes (Dunford *et al.*, 2014). This principle is often called by other names such as the *80/20 rule*, the *law of the vital few* or the *principle of factor sparsity*.

When applying this principle, particularly for new stations, if we assume that the majority of (say) incidents or suicides (about 80%) will occur at about 20% of the busiest stations or platforms, this will significantly change the evaluation. This is likely to be the case as the chance of having an even distribution of incidents over a network is low. There are always critical locations that record the highest number of incidents. In which case, those platforms, if identified, would be given higher priority and be assumed to have 80% of the incidents in the event that realistic local figures are not available, for example, in the case of new lines, etc.

To test this approach, the passenger entry and exit record obtained from LUL (2017) was studied to see if this principle could apply. It was discovered that 80% of network passenger flow occurs at about 40% of stations, whereas the top 70% of passenger flow occurs at about 27% of stations. This, even though not exactly 80/20, indicates that some of the stations contribute to a much greater effect (in this case, passenger flow).

When this kind of analysis is carried out on sensitive parameters, such as safety incidents, etc, it may result in a recommendation to consider installing PSDs only on those critical platforms and not on the entire network. This would significantly reduce the initial investment to deploy these doors. However, suicides in particular may not necessarily be avoided by preventing them at certain locations; it may just result in diverting them to other (perhaps nearby) locations. While this may or may not be the case, it is still an option worth considering when there is a high number of incidents recorded (or suspected) at particular stations.

6.6 Summary

The executable model developed to aid economic appraisals with regard to PSD deployment has been presented in this Chapter, with further analysis using hypothetical station characteristics formed from a combination of real data from reputable railway networks in different parts of the world. The analysis carried out in this Chapter provides guidance for prospective users of the model and discusses the possible results that the model would produce, and some of the ways that the results could vary when the stakeholders input specific data or change the assumptions.

The following Chapter summarises the whole thesis, pointing out the contributions made, key results obtained, critiques on challenging issues, and recommendations for further work.

Chapter 7

Conclusion

7.1 Preamble

In this thesis, a framework for the assessment of PSD deployment at metro stations has been developed and it has been demonstrated how platforms and stations can be assessed to justify, or otherwise, the fitting of PSDs.

This Chapter sums up the key conclusions reached, itemises the contributions made, provides recommendations to stakeholders, recognises possible issues of critique and suggests some further work.

7.2 Findings

The author of this thesis has identified and evaluated factors that are potentially affected by the deployment of PSDs on metro platforms, quantified the magnitudes of benefits and disbenefits, and provided guidance for stakeholders considering the installation of PSDs. The aim has been achieved, as demonstrated in various sections of the thesis and summarised in this Chapter. More so, this thesis has provided a deeper insight into the influence of PSDs on various railway factors and enables some key findings, as itemised below.

1. Installation of PSDs at metro stations affects numerous factors in the railway system. These include safety, HVAC energy consumption, service disruption, capacity, air quality, staffing, customer satisfaction and fare revenue. The factors

are too many to list here, but are mapped on a CLD produced as part of the thesis and presented in Figure 5.2. There are a total of 85 factors, of which 72% (61 factors) were quantified, and the remainder (28%) were roughly estimated.

2. The largest benefit of PSDs is in the form of greater safety achieved as a result of preventing suicides, trespasses and accidental falls occurring at the platform edge. Using the default values applied to the calculation, this amounts to an equivalent of nearly £7 million as a discounted cash flow benefit over the 35-year lifetime of PSDs on a typical metro platform, using a low *health discount rate* of 1.5%.

3. The second largest benefit is in optimisation of HVAC energy consumption. This is particularly high for regions where platforms require cooling, due to a very hot and/or humid climate, such as Dubai and Singapore (see Appendix C.3). On a typical platform, and again using default values, the discounted energy savings can amount to £4.3 million over the PSD lifetime.

4. The largest cost/disbenefit of PSDs is in the form of *Capacity* reduction occurring as a result of extending dwell time of trains due to additional seconds needed for door opening and closing. The monetary impact on capacity is estimated to cost £5.5 million on a typical platform. The second biggest cost is that of the PSD equipment purchase, which is around £3.4 million for a typical platform.

5. It was discovered that some of these factors stand a chance of influencing the decision to have PSDs on a particular platform when evaluated and combined. These are referred to as sensitive factors, namely safety (number of incidents), statistical value of life, HVAC energy consumption, dwell time (leading to an impact on capacity) and the cost of purchasing, installing and maintaining the doors.

6. The factors that are not likely to make significant impact on the rail system and are therefore unlikely to influence the decision of having platform doors were also identified and referred to as immaterial factors. These include aesthetics,

touch voltage potential, impact on emergency evacuation period, advertising potential, service reliability and reputation, accumulation of trash on the line, and disutility of travel.

7. There exists a causal relationship among the identified factors. The relationships are depicted in an SD model (Figure 5.2) showing the cause and effect alongside the impact (whether positive or negative), expressed as polarities attached to each of the factors on the model. The model formed the basis for arithmetic formulation, which is the next finding.

8. Mathematical formulae were developed to enable quantification of the identified factors in their respective units. The values were then translated into a common unit of money to enable comparison of impact. These equations can be used to estimate the quantities of these factors both as a process of evaluating the viability of PSDs, and in other scenarios for which the factors need evaluating.

9. For PSD evaluation purposes, the default values of many factors were populated from a combination of real data obtained from prominent rail networks. These default values (Appendix B; Figure B.1) can serve as a reference point or a benchmark when specific real local data are not available, for example in the case of new-build stations.

10. Economic evaluation of PSDs can be made using the executable model developed as part of this research and presented in Chapter 6. The model can be customised to reflect local conditions to enable bespoke results which can predict the overall result (whether gain or loss) of providing PSDs on particular platforms. Note that the model is not meant to make the decision; it exists rather to inform decision makers and therefore maximise the chance of making a rational decision.

11. Using the developed model with all default values as the input, therefore forming a hypothetical platform with the characteristics of a typical platform that is comparable to most platforms on various rail systems, statistical results were generated to predict the effect if PSDs were considered for deployment on that

platform. Based on the assumed numbers, the results yielded a total cost of £11.8 million and a total benefit of £11.5 million, to the nearest hundred thousand pounds, over the 35-year lifetime of the PSDs, based on a standard discount rate of 2.68% and a low health discount rate of 1.5%. The associated BCR was calculated to be 0.98 which is just under equilibrium but indicates an overall loss if PSDs were to be fitted, leading to an NPV of -£271,000 to the nearest thousand pounds. However, stakeholders may be required by law to ensure safety (RSSB, 2019) by reducing risks to ALARP. This may necessitate the need to do the work despite it having a slight overall disbenefit. This is the case in most UK organisations following the Edwards vs National Coal Board case back in 1949. However, in order for the case of PSDs to be considered on this ground, there has to be a safety concern (for example, an alarming record of platform incidents) which necessitates taking a safety measure.

12. According to the statistical results, the model suggests that the business case for having PSDs on every platform is weak. This could be the case for platforms having characteristics similar to those of the hypothetical platform. However, when evaluating multiple platforms, it may be the case that some key factors such as safety may be higher in some stations compared to others. In that case, the Pareto principle of 80/20 or a local variation of that may be most suitable for the analysis.

Note that the stakeholders impacted by most of the cost components are the infrastructure owners who manage and run the stations. The biggest costs are those for PSD equipment, installation and maintenance, and the impact on capacity. On the other hand, the largest gain accrues to society (passengers and the general public) in the form of enhanced safety through the prevention of fatalities and injuries. The infrastructure owners mainly benefit from the savings in HVAC energy and, to some extent, the prevention of service disruption and fare revenue associated with that. The implication of these exogenous societal benefits and the indigenous operator/funder cost is that, the funding for the PSDs may be difficult to justify when considering the financial gains that particularly accrue to the operator/funder. It is therefore imperative to evaluate these in a lot more detail when considering to install PSDs.

Many of the findings listed above are applicable to mainline railways also but must be reviewed on case-by-case basis.

7.3 Conclusions and Guidance for Stakeholders

The key conclusions reached as a result of the findings itemised in Section 7.2 are listed below. Note that these conclusions can serve as guidance for stakeholders considering the installation or evaluation of PSDs.

1. The cost of PSD equipment, installation and maintenance is a significant barrier to their installation on metro systems. The price range obtained from inquiries in the western world points towards an upfront cost of £13,000 and up to £18,000 per linear metre of screen work. This excludes maintenance which comes periodically and amounts to an additional £1.4 million per platform over the PSD's lifetime (typically 35 years).

2. The impact of PSDs on platform safety by preventing suicides, trespasses and accidental falls provides the largest benefit emerging from their installation. On a typical platform, these safety benefits can accrue to just under £7 million through the 35-year lifetime of the PSDs, based on the assumed numbers. Metro systems considering PSDs should evaluate (or estimate in the case of a new build) safety incidents at the stations under question. If the number of safety incidents is high, then deploying PSDs as a countermeasure is probably justifiable. This would be more pronounced in countries where the value of preventing a fatality is higher, e.g., the US (£7 million[1]), UK (£1.9 million), etc. For countries where the value of life is not that much, for example Burundi and Liberia (£36,000 and £53,000

[1]USD 10 million equivalent at 0.81 per GBP. Data source: Kniesner and Viscusi (2019)

respectively[2]), PSDs would probably not be justified even if there is a high incident record. However, justification may come from having a PSD supply at a lower price than used in this research, perhaps lower than it currently is in Asian countries, and there is some anecdotal evidence that PSDs are much cheaper in China due to significant economies of scale.

3. Having mentioned the sensitivity to the value of life, other sensitive factors in the economic appraisal of PSDs include platform incident records, energy requirements for HVAC, the cost of PSD equipment, and the change in dwell time. All these vary from one system/station/platform to another. In addition, the final PSD model developed is also sensitive to these factors. Small changes in the sensitive factors can affect the final results significantly, for example by up to four times for VSL, as low as one-third for incidents and as high as five times for HVAC. Sensitivities are analysed and presented in Section 6.4.3. Stakeholders should therefore consider these sensitive factors and their local application when evaluating the viability of PSDs.

4. Energy consumption for HVAC is another significant factor that could sway the decision to have PSDs. While this is of low significance in moderate climates, it is of high importance in hot climate regions such as Singapore, Saudi Arabia and the United Arab Emirates. In these regions, PSDs are likely to be justified even for above ground stations, considering the enormous amount of energy required to maintain an acceptable temperature in station environments. On a typical platform where PSDs reduce, say, 36% of energy consumption (can be higher in very hot climates), the benefit in terms of money can amount to £4.3 million over the PSDs' lifetime. Refer to Figure 6.5 for a scale comparison of the magnitude of both benefits and costs associated with PSDs.

5. If PSDs are not well integrated with the SCS to alleviate latency in opening and closing doors, the impact on dwell time can limit train frequency, which has a

[2] USD 45,000 and 65,000 respectively at a rate of 0.81 to GBP. Source: Viscusi and Masterman (2017)

detrimental impact on the capacity of the service. This can contribute to congestion and dissatisfaction of customers. In the event of PSDs extending dwell time by 5 seconds, line capacity can be reduced by one train every hour, leading to an estimated discounted loss of £5.6 million over the PSDs' lifetime. Therefore, if PSDs are evaluated as being desirable, measures should be put in place to ensure a minimal impact on dwell time.

6. For evaluation of new metro stations, where the installation of PSDs is being considered for most or all stations, application of the Pareto principle would yield the most economic results and is particularly suitable for safety factors. A forecast of safety incidents can be carried out for all platforms, using factors such as anticipated passenger flow, proximity of psychiatric centres to stations, previous geographic record of suicides, etc. It can then be projected to identify the stations most vulnerable to safety occurrences. These vulnerable stations could be fitted with PSDs while leaving the rest without. Using this approach can achieve majority of the benefit with much lower cost; not necessarily 80/20 as suggested by Pareto, or 70/27 as in the LUL analysis (see Section 6.5), but evaluation should seek to get the best balance. This then enables an optimum use of resources, particularly for systems where funding is an obstacle to the PSD project. Given that preventing suicides contribute largely to the benefits, stakeholders should be aware and take account of the possibility of displacement of suicide occurrences to other locations.

7. For existing stations, the same Pareto principle can be applied using real incident data to identify the vulnerable stations. This approach was tested on the London Underground network, and it was discovered that 70% of all passenger flow occurs at only 27% of the 270 stations (see Section 6.5). If PSDs were to be fitted in those 27% of stations, 70% of passengers would be protected from platform incidents by investing only 27% of the network-wide PSD cost.

8. As the most significant PSD benefit accrues to passengers and the general public

by shielding them from PTI risks, and most of the costs are incurred by the infrastructure owners/managers, the question of who pays for PSDs remains controversial. Ideally, it would be the infrastructure managers, but because passengers and the public get the most benefit, the cost can be shared by both, in terms of a slight increase in fare (as is the case for Hong Kong) or from tax payers' money, otherwise known as the public fund (as is the case for Crossrail), respectively.

To make it more explicit, the key conclusions are summarised thus;

1. PSDs have a high initial cost of installation.
2. The largest benefit of PSDs is the prevention of safety incidents. This is very sensitive to the monetary value of life.
3. Some factors are sensitive to PSDs evaluation. These include incident record, energy, cost of PSD equipment and delays.
4. Impact on energy consumption could influence the decision to have PSDs especially in hot climate regions.
5. Alleviating latency between PSDs and train doors is crucial to maintaining dwell time and by extension, capacity.
6. Application of *Pareto principle* yields the most economic decision of where to install PSDs, but this does not address the suicide displacement issue.
7. For existing stations, the impracticality of *Pareto principle* prevails. There is need to evaluate the best balance.
8. Passengers and the general public get the most benefits from installing PSDs.

7.4 Thesis Contributions

This thesis has made several contributions, both to the current literature in the domain of PSDs and to the rail industry. Key contributions are itemised as follows:

1. The provision of a framework (methodology) that can be adapted for evaluation purposes, not only for platform doors but also for other systems and engineering-related phenomena within the railway industry. This, in summary, entails the identification process that was followed, the structuring of the whole scenario to reveal the cause and effect relationships, followed by arithmetic quantification and conversion into a common unit, and lastly predictive model development. This has not been done before in any PSD-related academic work or, so far as the author can tell, in any PSD project evaluation.

2. The creation of a checklist for PSDs, the elements of which were identified through the literature, industry and systems thinking and verified through consultation with industry stakeholders. The list (see Appendix E) can be used by decision makers as a reference while carrying out an evaluation to decide whether or not to have PSDs. This enables an enhanced understanding of the various impacts that can occur as a result of the PSDs deployment.

3. The development of a causal structure in the form of a CLD that depicts the various relationships among the affected factors. This could be very useful in the early stage of PSD consideration to know what might be affected and how, so that necessary measures can be taken to maximise benefits and deal with challenging issues.

4. Quantification of factors within the rail industry that are affected by PSDs. This enables not only the estimation of these factors in their respective units, but also translation of those estimates into a common unit of money, which makes it possible to compare the significance of such impacts between multiple variables with different base units.

5. The provision of a PSD evaluation model that can be used to evaluate platforms using local data as the input to generate economic parameters in terms of cost implications and the money equivalent of derived benefits, which could be useful while considering having PSDs.

6. Recognition of the factors that may have the most significant impact, hence referred to as the sensitive factors. These factors will influence the decision to have PSDs and therefore require careful consideration with reference to the local issues, e.g., the rate of safety-related incidents, statistical value of life, regional climate that necessitates heating or air conditioning, etc.

7. Sensitivity Analysis supplied to aid understanding of the impact that the sensitive variables can have on the overall results when varied in the PSD appraisal. These sensitivities are presented in Figure 6.7 and table 6.4.

8. Provision of guidance for stakeholders (Section 7.3) that can be used when undertaking economic evaluation for PSDs.

The boundary conditions defined through testing the hypothesis are that, once the positive and negative factors in the executable model have been evaluated, it can serve as a justification for fitting or not fitting PSDs, based on whether the BCR and NPV results satisfy the investment requirements of the company/system considering the installation of doors.

To summarise, the researcher has reached the research objectives by:

1. Identifying the factors affected by PSDs: The identification process is described in Section 3.3 and the factors identified are listed in Appendix E.

2. Carrying out a CBA: The results generated using the models developed were used in conducting the CBA to reveal the overall cost, overall benefit, BCR and NPV. These are all presented in Section 6.4.2.

3. Estimating the whole-life PSD disbenefits: These are estimated individually for each disbenefit factor and presented in Figures 6.5 and 6.6.

4. Estimating the whole-life PSD benefits: The benefits were also estimated individually for the positive factors and presented in Figures 6.5 and 6.6.

5. Developing the valuation methodology: The method developed and used in this thesis serves as the valuation methodology for the PSDs. This method is described in Chapter 3.
6. Developing guidance for stakeholders: Stakeholders considering to install PSDs can find guidance from this thesis which is summarised in Section 7.3, but Chapter 7 as a whole provides a more detailed guidance.

7.5 Critique

While this thesis has considered various factors with regard to PSD deployment, there is a possibility, however, of identifying areas that require improvement either in the identification of factors, relationships or something entirely different. The Author has identified some issues worthy of mentioning as follows.

Having recognised a total of 85 factors that could be influenced by deploying PSDs (see Figure 5.2), critique suggests that there may be some missed factors. The author acknowledges that future studies may find other factors in the railway system that are also affected, for example novel/innovative SCSs in the future. However, if any factors were to be discovered, they could be incorporated into both the SD and executable models, once the causality and arithmetic relationships are established respectively.

Some of the factors identified and defined as immaterial may in some circumstances be more significant than stated, and may therefore have an influence on the final CBA. While the analysis undertaken by the author has shown that they are generally not significant when considering PSDs, the possibility of incorporating them into the analysis remains. This is because the framework developed can be customised to suit the requirements, changes and policies of any railway system, including the opportunity of integrating such factors in the spare cells provided in the final model. There is scope for three factors to be added without having to change the model.

Results presented in this thesis were generated from the input data used; the hypothetical station. These results can vary when different values are used, especially for the sensitive factors discussed in Section 6.4.3. NPV and BCR will also change if a different discount rate is used for the analysis.

The models developed in this thesis are not in themselves capable of making the PSD decision. They are support tools intended to supply meaningful information. The decision whether to have PSDs may be influenced by other factors, not just the CBA, for example, reputation (if incidents are frequent, even if the cost of averting them is higher than the benefits), legality (law imposed to necessitate putting in place some countermeasures) and morality (moral responsibility to avert harm to public/passengers or the feeling that it is the right thing to do despite the cost). Other factors that may influence the decision include business, political and other social factors. Notwithstanding that, this thesis has established a mechanism that supports economic and other forms of evaluating PSDs.

7.6 Recommendations

The author of this thesis has classed some of the factors identified as being affected by PSDs to be of less significance. Hence, they were not included in the final economic evaluation. In line with that, when evaluating a particular system for which the stakeholder feels it is important to quantify all factors for reasons known to them, the factors not included can then be quantified in accordance with the suggested methods in the estimation presented in Appendix D. This would enhance the level of detail and give the decision makers more information.

The executable model contains default values for the input factors. In order to ensure the relevance of the results for a specific case, it is recommended to avoid such default values. The values can, however, be used to enhance understanding of the magnitude of the impact that the PSDs would create. They can be used in specific cases to fill any gaps in knowledge at the early stages of evaluation.

Having established the various valuing procedures and models based on metro systems, it is recommended to make necessary adjustments when using the models for light rail, regional and HSR systems. It is also recommended to use data that correspond to the type of doors proposed, for instance not assuming all incidents would be averted by half-height PSDs if the PSD cost inserted is for half-height doors, etc.

For PSD suppliers, it is recommended that they put effort into designing PSD systems that can synchronise with train doors for both opening and closing phases to avoid latency, thereby eradicating the additional dwelling time. This would minimise or eradicate the impact on capacity, particularly for busy rail systems.

7.7 Further Work

Considering the recommendations made, the next step in taking this research forward is to apply the developed executable model to a real project evaluation where realistic local figures would be used to generate results specific to the network being tested. The use case will enable practical use of the model and may generate feedback for possible improvement, particularly from the three main stakeholders, namely decision makers, station/platform designers and suppliers bidding for a PSD project.

A more in-depth sensitivity analysis can be carried out by potential users to ensure identification of the most sensitive factors specific to their scenario and find out if there are any other factors that need to be treated as sensitive.

Another way of taking this work forward is through modelling for different types of PSDs. The procedure and models can be customised to come up with new versions to estimate the level of impact based on the type of PSDs chosen, and be able to advise on the best option - whether full-height, half-height or simply safety gates, depending on the local data.

Appendix A

Samples of System Dynamics Diagrams

System Dynamics (SD) discussed in Chapter 2, uses some graphical tools to model and understand the behaviour of complex systems. These tools are explained in Section 2.4. This appendix therefore presents a set of samples of the SD tools used in the academic research appropriately cited in Figure A.1:

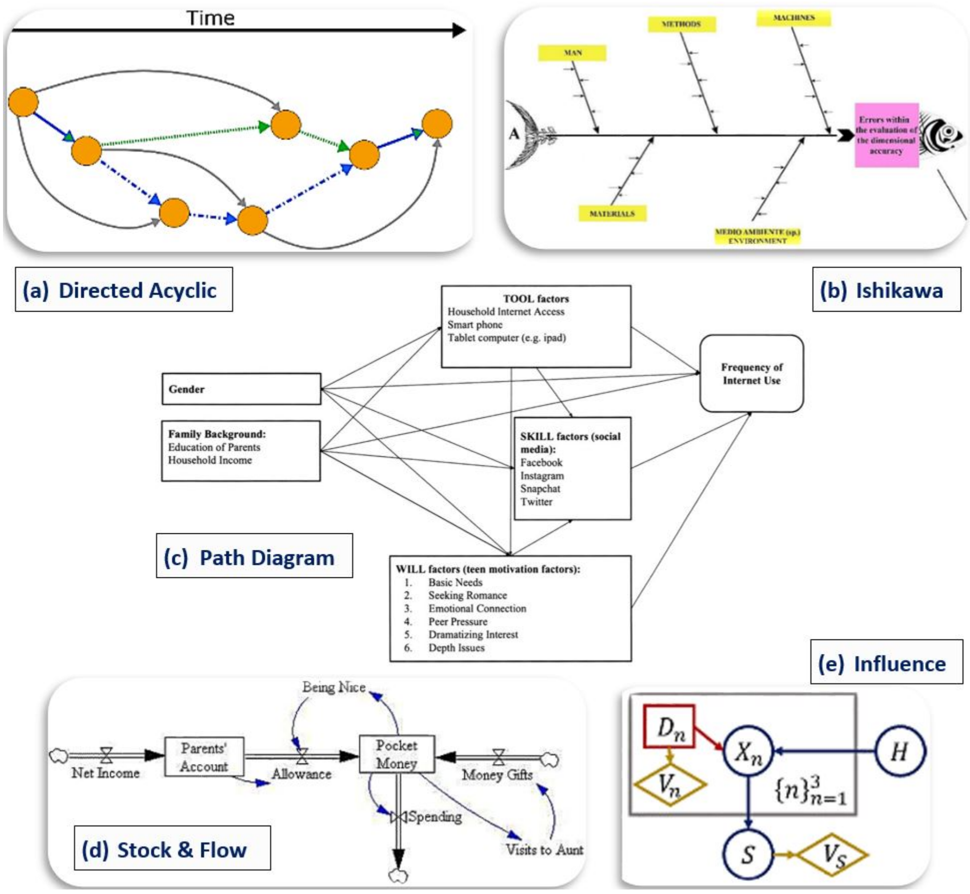


FIGURE A.1: Samples of SD Tools from Studies by [a] Evans *et al.* (2019), [b] Liliana (2016), [c] Grant (2019), [d] Binder *et al.* (2004) and [e] Byun and Song (2019)

Appendix B

Characteristics of the Hypothetical Station

The hypothetical station used for the pilot CBA discussed in Chapter 6 has the characteristics presented in Figure B.1. These are formed from a combination of real data collected from notable rail systems across the globe. The data are merged for two purposes. First, to preserve confidentiality of these rail systems while still making use of real data. Second, to form average values that can reflect a typical station which is not on a particular rail network but can have bits of characteristics similar to a variety of networks.

The input values shown below (Figure B.1) are the same as those proposed as default values in the executable model as a form of benchmark for when real data are not available to a potential user of the model intending to evaluate a particular platform on a particular metro system.

The pilot results obtained using these inputs are presented and discussed in Section 6.4.2.

Please key in the data in '***Your Input***' column

ePSD Model Please indicate **number of platforms:** 2 Bottom ↓

S/N	Parameter	Unit	Your Input	Values in Use	Default Value?
	Platform Incidents				
1	Avg. platform trespass	FWI/platform-yr		0.0031	✓
2	Avg. platform accidental falls	FWI/platform-yr		0.0151	✓
3	Avg. platform suicides	FWI/platform-yr		0.1117	✓
4	Avg. platform mantrap incidents	FWI/platform-yr		0.0009	✓
	Station Particulars				
5	Number of platform staff	staff/platform		1.00	✓
6	Avg. number of platforms per station	platform/stn		2.00	✓
7	Avg. station dwell time	sec		32.50	✓
8	Anticipated PSDs' effect on dwell time	sec		5.02	✓
9	Avg. daily station operation hours	h/day		19.70	✓
10	Single journey fare	£/journey		1.86	✓
11	Avg. journey length on the network	min/journey		39.96	✓
12	No. of train door sets per platform	doors/platform		28	✓
13	Frequency of train at station (capacity)	tph		27.60	✓
14	Number of train stops along the line	platform		28	✓
15	Avg. platform length	m/platform		179.52	✓
	Staff Information				
16	Hourly overtime pay rate of train driver	£/h		26.70	✓
17	Weekly working hours of train driver	h/week		35.00	✓
18	Number of DCR staff required	staff		0.83	✓
19	Annual Salary of DCR staff	£/yr		29,133	✓
20	Annual PSD/DCR Staff training cost	£/yr		0	✓
21	Workforce time lost due to incidents	weeks/FWI		6.00	✓
	Energy Information				
22	Avg. station HVAC energy consumption	kWh/yr		9,765,619	✓
23	Unit cost of energy	£/kWh		0.1199	✓
24	Daily standing charge for station energy	£/day		0.2620	✓
25	Anticipated HVAC savings with PSDs	%		36.11%	✓
26	Auxiliary train power	kW		604.00	✓
	Operational/Others				
27	Avg. service disruption rate	min/FWI		95.00	✓
28	Unit cost of delay minute	£/min		250.00	✓
29	Rate of lost customer hours	h/FWI		12,209.00	✓
30	Rate of workforce shock/trauma	-		0.0050	✓
31	Change in platform air pollution (PM_{10} etc)	$\mu g/m^3$		43.78	✓
32	Damage cost of pollutants	£/person-yr/µg/m3		25.71	✓
33	Change in ambient platform noise	dB		6.10	✓
34	Damage cost of noise annoyance	£/person-yr/dB		5.66	✓
35	Value of preventing a fatality (VPF)	£/FWI		1,946,000	✓
36	Standard discount rate	%		2.68%	✓
37	Health discount rate	%		1.50%	✓
38	Maximum passenger capacity per train	p/train		1,525	✓
39	Average (train) riding occupancy	%		33%	✓
	PSD Information				
40	PSDs purchase & installation cost	£/m		18,774	✓
41	PSDs maintenance cost per linear meter	£/m-yr		357	✓
42	Cost of PSDs half-life overhaul	£/m		6,648	✓
43	Extra function cost	£/platform		0.00	✓
44	PSDs Power consumption per door set	kW		0.82	✓
45	Lifetime of PSDs (also, years of analysis)	yrs		35.00	✓
46	Cost of taking the PSDs down at lifetime	£/m		1,277	✓
47	Salvage Value of the PSDs	£/m		1,277	✓
	Parameter 1	unit		0.00	
	Parameter 2	unit		0.00	
	Parameter 3	unit		0.00	

Top ↑

FIGURE B.1: Characteristics of the Hypothetical Station (Author)

Appendix C

Platform Barriers

This appendix presents images of the different types of platform barriers discussed in Chapter 4. Also presented in this appendix are samples of the *emergency release mechanisms* used for different PSD designs, and some figures for the *local control panel*.

C.1 Platform Safety Gates

PSGs are simpler forms of platform barriers installed not only on metro but on other systems such as light rail ([a] in Figure C.1) and the famous Shanghai magnetic levitation (maglev) train service ([b] in the Figure).

FIGURE C.1: Platform Safety Gates on [a] Singapore LRT (Author) and [b] Shanghai Maglev (Jack, 2018)

C.2 Half-Height PSDs

Half-height platform doors were retrofitted on above ground platforms in Singapore; after this, passengers complained to the authorities that the platforms were hotter than they used to be prior to the PSD retrofit. This necessitated a provision for additional ventilation on the platforms. Ceiling-mounted fans of various sizes and type were then installed to enhance the platform ventilation; an example of these is shown in Figure C.2.

FIGURE C.2: Half-height PSDs in Above ground Stations of the East-West MRT Line, Singapore, Featuring Platform Ventilation Fans [a, b] (Author)

C.3 Full-Height PSDs

Figure C.3 shows examples of full-height PSDs on systems. It is worth mentioning that the LUL PED [d] does not have air sealing at the top of the doors; it therefore allows exchange of air between the platform and the tunnel.

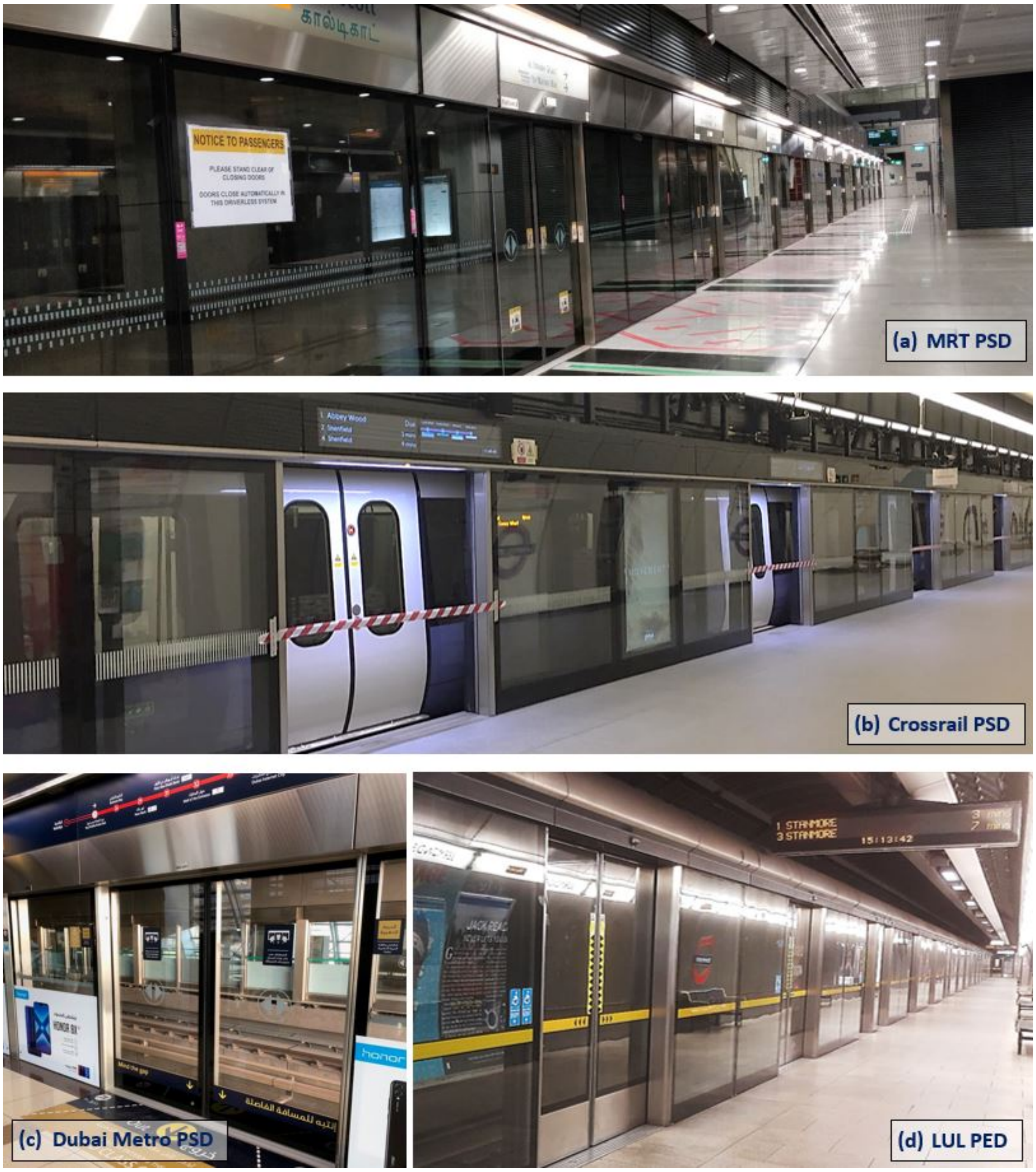


FIGURE C.3: Full-height PSDs on [a] Circle MRT Line, Singapore (Author); [b] Elizabeth Line, London (Crossrail, 2019); [c] Red Line, Dubai Metro, UAE (Jack, 2019); and [d] Jubilee Line, London (Author)

C.4 Vertical Platform Barriers

Due to the restrictions of conventional PSDs on train door positions, the idea of having doors that open vertically exists to allow the use of various train configurations on the same platform despite having the platform barrier. Vertical PSDs are still not common today but are in use in some places, most of which are trial installations. Examples of these are given in Figure C.4.

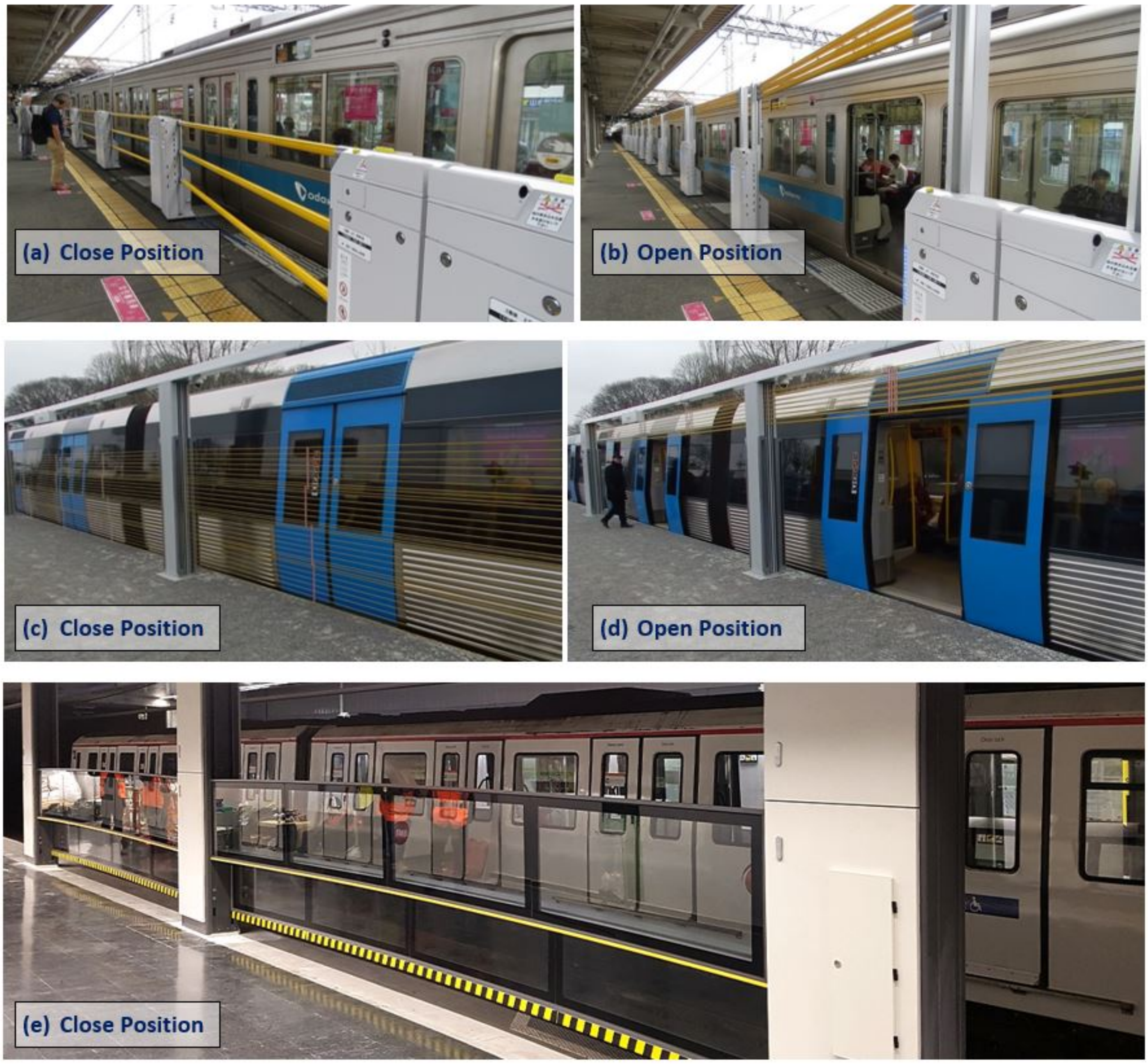


FIGURE C.4: Vertical Platform Barriers [a, b: Aikō-Ishida Station, Japan (Kusakamachi, 2017)]; [c, d: Daegu subway, Korea (Svartmetall Sverige, 2015)]; and [e: Can Cuias Station, Spain (Cho and Shin, 2019)]

C.5 PSDs in Airports with Automated People Movers

As explained in Section 1.1.1, PSDs are popular in Airports where people movers are in use. Figure C.5 shows some examples.

FIGURE C.5: PSDs in [a] Pisa Airport APM, Italy; [b] Air-Rail Link of Birmingham Airport, UK; and [c] Skytrain at Changi Airport, Singapore (Author)

C.6 Emergency Release Mechanism (ERM)

ERMs are manually operated door release handles located on the trackside of the PSD doorways. They are for passenger use in case of emergency and have different designs as shown in Figure C.6.

FIGURE C.6: Emergency Release Mechanism on [a, b] Singapore MRT; [c] Jubilee Line, LUL; and [d] Line M1, Copenhagen Metro (Author)

C.7 Local Control Panel (LCP)

Platform LCPs can be used by staff and usually also by passengers to control doors when they fail to open or close, and in an emergency. LCP designs differ from one supplier to another. Examples are shown in Figure C.7.

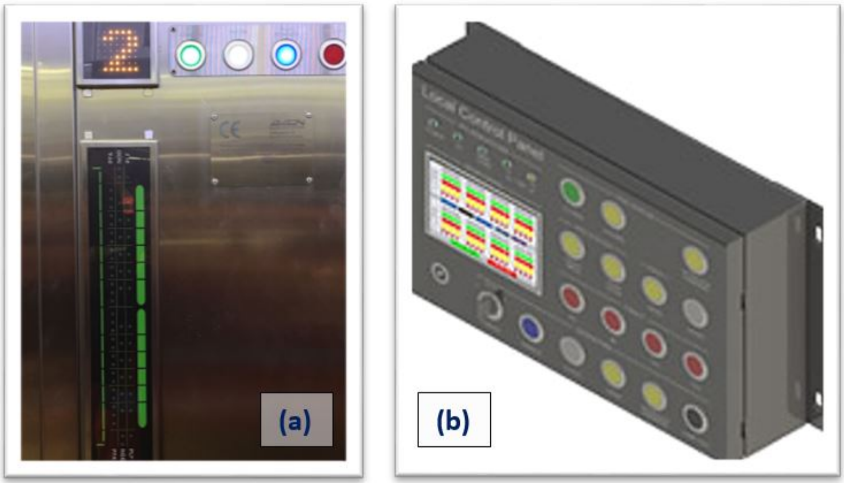


FIGURE C.7: Local Control Panel on [a] Stockholm City Line, Sweden (Author) and [b] NRT (2019b) Product Specification

Appendix D

Estimate of the Scale of the Unquantified Factors

The factors deemed insignificant were not comprehensively quantified for inclusion into the executable model, for the reasons explained against each factor in Section 5.5. These factors were, however, estimated to ascertain their level of impact had they been re-incorporated into the model. The estimates are presented in Table D.1, showing the corresponding justification behind each estimate in the comment column.

TABLE D.1: Crude Estimate of the Unquantified Factors (Author)

S/N	Factor	Value (£)	Comment
1	Room for new rolling stock	0.00	Depends on circumstances arising; could be zero, or very significant – here assumed zero.
2	Aesthetics/ Attractiveness	0.00	Depends on passenger preference, and type of platform – side (may be +ve) or island (may be -ve) platforms.
3	Sound quality of platform announcements	0.00	Attracts no financial benefit.

Continued on the next page

Table D.1 – Crude Estimate – *continued from the previous page*

S/N	Factor	Value (£)	Comment
4	Crowd control	280	Assuming that PSDs would provide a 1% increase in platform capacity, there would be a 1% decrease in crowd level. According to a study conducted by Kroes *et al.* (2014), passengers are willing to pay €8 to reduce the crowd level from peak to off-peak level. Reducing the crowd level by 1% then would equate to 1% of €8 which is equal to €0.08. However, this is for on-board crowding. Platform crowding would be just a fraction of that since it is just for few minutes or seconds. Assuming 1 min waiting time and an average of 40 min travel time, the value for platform crowding would be 1/40 of €0.08 = €0.002. This, when multiplied by daily passenger flow of 15,262 (average daily entry of all LUL stations), yields €30.524 per station or €15.262 per platform (assuming two platforms per station). €15.262 is equivalent to £14 (Aug. 2019 rate: €1 = £0.92). The NPV of this in 35 years at a 3.5% rate is £280.
5	Trash on the line	0.00	Same as cleaning. Trash accumulates either on the trackside (without PSDs) or on the platform (with PSDs). Both require cleaning. However, the cost of cleaning rubbish from the track and the platform is not likely to be the same. Nevertheless, the difference, when articulated in terms of the PSDs impact on rubbish accumulation, is considered insignificant by the Author in comparison to factors quantified such as the safety.

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Table D.1 – Crude Estimate – *continued from the previous page*

S/N	Factor	Value (£)	Comment
6	Sense of security to the waiting passengers	720	Hamm (2017) estimated the cost of feeling safe for a family to be USD 20,872.01 over 10 years, i.e. $2,087.201 a year (£1,716 at 0.82 $ to £ rate). This is £0.00326 a minute. With US average household occupancy of 2.52 (Statista, 2019), this is £0.00129 per person. Assuming (15,262/2 = 7,631) passengers spend an average of 1 minute on the platform, and 20% of them around the edge feel a bit safer due to PSDs, the value is £1.97 a day = £720 a year.
7	Rate of smoke spreading from tunnel to platform	0.00	A factor leading to the safe egress time, hence requiring no quantification.
8	Available safe emergency egress time	0.00	By holding back smoke in the tunnel, PSDs allow safe egress time for passengers on the platform, whereas they compound the smoke in the tunnel, increasing the risk of suffocation for passengers on board, vice versa if the fire is from the platform. This is hence considered to have a neutral (and therefore zero) impact.
9	Emergency evacuation period	0.00	Depends on where the emergency starts, on board (negative impact) or on the platform (positive impact). PSDs are therefore assumed to have zero impact on the evacuation period (the **time** it takes to evacuate people).
10	Touch voltage	0.00	Depends on PSD earthing: either to station earth (+ve for passengers on the platform, -ve for passengers crossing the PTI), or to traction earth (-ve for passengers on the platform, +ve for passengers crossing the PTI).
11	Wind surge	0.00	Wind surge creates discomfort and poses the risk of passengers losing their balance, in addition to the risk of luggage being dragged. Until that happens (which would be counted among PTI incidents), the financial consequences of the surge can be considered negligible.

Continued on the next page

Table D.1 – Crude Estimate – *continued from the previous page*

S/N	Factor	Value (£)	Comment
12	Service reputation	0.00	The ratio of LCH with and without PSDs is (11/1596) = 0.0069. Hence, disruption with PSDs is just 0.69% of that without it. Therefore, only a small fraction of the service reputation relates to avoidance of disruptions; thanks to PSDs.
13	Good passenger behaviour	-	The part that improves door utilization time is included in the dwell time quantification. Another part is the slight comfort to passengers which contributes to the utility of the travel discussed herein.
14	Disutility of travel	0.00	A combination of part of good passenger behaviour (+ve comfort) and passenger shock/trauma (-ve discomfort). The result would approach zero.
15	Passenger shock/trauma	0.00	Discomfort of witnessing incidents would be minimal if not directly involved either as a cause (e.g., Driver) or as a victim. Hence, it contributes only to the disutility of travel.
16	Customer dissatisfaction due to delays and cancellations of trains	354	Annual calculated delays in minutes with and without PSDs are 0.09 and 12.42 min/yr respectively, resulting in a difference of 12.33 min/yr. In the UK, delays are eligible for compensation only when they are 15 min or more (DfT, 2018a), qualifying for 25% of the ticket cost. Hence, using delay compensation to estimate satisfaction, it will be zero for a delay of 12.42 min. However, assuming this is paid for, say, a half-full train (762 passengers), the amount would be (762 $\times$ 0.25 $\times$ £1.86) = £354 per year, where £1.86 is a single journey fare.
17	Overall service disruption	-	The sum of two disruptions, disruption due to incidents (already quantified in the model) and disruption due to retrofitting (below).
18	Service disruption due to retrofitting	0.00	Zero for new build. Can be estimated further for retrofitting.

Continued on the next page

Table D.1 – Crude Estimate – *continued from the previous page*

S/N	Factor	Value (£)	Comment
19	PSD retrofitting	-	A major process (not effect) which occurs only for existing stations. It is on the CLD to reflect the retrofitting process for which the model can be used to estimate the financial figures.
20	Excess platform waiting time	-173	Rough estimate using the public transport value of time (Kroes *et al.*, 2014) of £16.284 per hour (£0.0045 per sec) for the 5 sec delay, to the number of passengers, we have (0.0045 $\times$ -5 $\times$ 15,262), which is -£345 or -£173 per platform.
21	Service reliability	0.00	Reliability is greatly influenced by the operating conditions. The effect of PSDs on service reliability is quite negligible.
22	Passenger information screen	0.00	Same function as hanging screens on platform, simply better aesthetics.
23	Advert potential	0.00	Same function as adverts on the trackside wall, but a bit more modern and could be digital depending on the design.
24	Announcement potential	0.00	Would simply replace the platform speakers with no extra benefit.

Appendix E

Checklist of PSD Factors

A total of 85 factors were identified as being affected by the deployment of PSDs; 61 of these were included in the quantification process, for which numerical values converted into money were obtained. The other 24 factors were not included in the quantification process for the reasons outlined in Appendix D. These factors are all listed in tables E.1 and E.2 respectively.

TABLE E.1: Checklist of the Quantified PSD Factors (Author)

S/N	Factor	Used in the Estimate of
1	Accidental fall	Safety
2	Capacity	Capacity
3	Cleaning cost	Staffing
4	Cost of DCR devices and furniture	PSD Cost
5	Cost of DCR structure	PSD Cost
6	Cost of integration, testing & commissioning	PSD Cost
7	DCR staff	Staffing
8	Decommissioning cost	Decommissioning
9	Door closing time	Capacity
10	Door opening time	Capacity
11	Dynamic dwell time	Capacity
12	Energy consumed by PSD	Energy
13	Energy Requirements (overall consumption)	Energy
14	Entrapment	Safety
15	Fare revenue	Fare
16	Half-life overhaul	Half-life
17	Homicide/assault	Safety
18	Incident record (overall)	Safety

Continued on the next page

Table E.1 – Checklist 1 – *continued from the previous page*

S/N	Factor	Used in the Estimate of
19	Need for staff training	Staffing
20	On-board air quality	Air Quality
21	Optional PSD function – Media	PSD Cost
22	Optional PSD function - Gap closing	PSD Cost
23	Optional PSD function - Heating/cooling	PSD Cost
24	Optional PSD function - LED lights	PSD Cost
25	Optional PSD functions (overall)	PSD Cost
26	Overall cost of DCR	PSD Cost
27	Overall cost of the PSD	PSD Cost
28	Overall dwell time	Capacity
29	Overall PSD installation cost	PSD Cost
30	Passenger RORI flow time	Capacity
31	Platform air conditioning requirements	Energy
32	Platform air quality (overall)	Air Quality
33	Platform capacity	Platform Capacity
34	Platform Carbon dioxide level	Air Quality
35	Platform climate control	Energy
36	Platform heating requirement	Energy
37	Platform Nitrogen Oxides level	Air Quality
38	Platform particulate matter (PM) level	Air Quality
39	Platform Radon level	Air Quality
40	Platform staff	Staffing
41	PSD equipment purchase cost	PSD Cost
42	PSD maintenance cost	Maintenance
43	PSD on-site installation cost	PSD Cost
44	PSD trial (off-site) installation cost	PSD Cost
45	Redundant train energy consumption	Energy
46	Required PSD power supply devices	PSD Cost
47	Safety & security (overall)	Safety
48	Salary budget	Staffing
49	Salvage value	Salvage
50	Service disruption due to incidents	Disruption

Continued on the next page

Table E.1 – Checklist 1 – *continued from the previous page*

S/N	Factor	Used in the Estimate of
51	Smoke exhaust system requirement	Energy
52	Staffing (overall)	Staffing
53	Static dwell time	Capacity
54	Suicide	Safety
55	Train delays & cancellations	Disruption
56	Train noise on the platform	Noise
57	Trespass	Safety
58	Tunnel PM	Air Quality
59	Ventilation systems requirement	Energy
60	Workforce shock/trauma	Safety
61	Workforce time lost	Staffing

TABLE E.2: Checklist of the Unquantified PSD Factors (Author)

S/N	Factor
1	Advert potential (vertical screens)
2	Aesthetics/attractiveness
3	Announcement potential (sound devices)
4	Available safe emergency egress time
5	Crowd control
6	Customer satisfaction
7	Disutility of travel
8	Emergency evacuation period
9	Excess platform waiting time
10	Good passenger behaviour
11	Overall service disruption
12	Passenger information screen
13	Passenger shock/trauma
14	PSD retrofitting
15	Rate of smoke spreading - tunnel to platform
16	Room for new rolling stock type
17	Sense of security to the waiting passengers
18	Service disruption due to retrofit
19	Service reliability
20	Service reputation
21	Sound quality of platform announcements
22	Touch voltage risk
23	Trash on the line Neutral
24	Wind surge

Appendix F

Screenshots from the PSD Model

This appendix contains a set of screenshots from the generic PSD model described in Chapter 6. Input data used are those of the hypothetical station given in Appendix B; whereas results obtained are shown in Figure 6.4. Please refer to Section 6.2.1 for details on each of the sheets contained in the model.

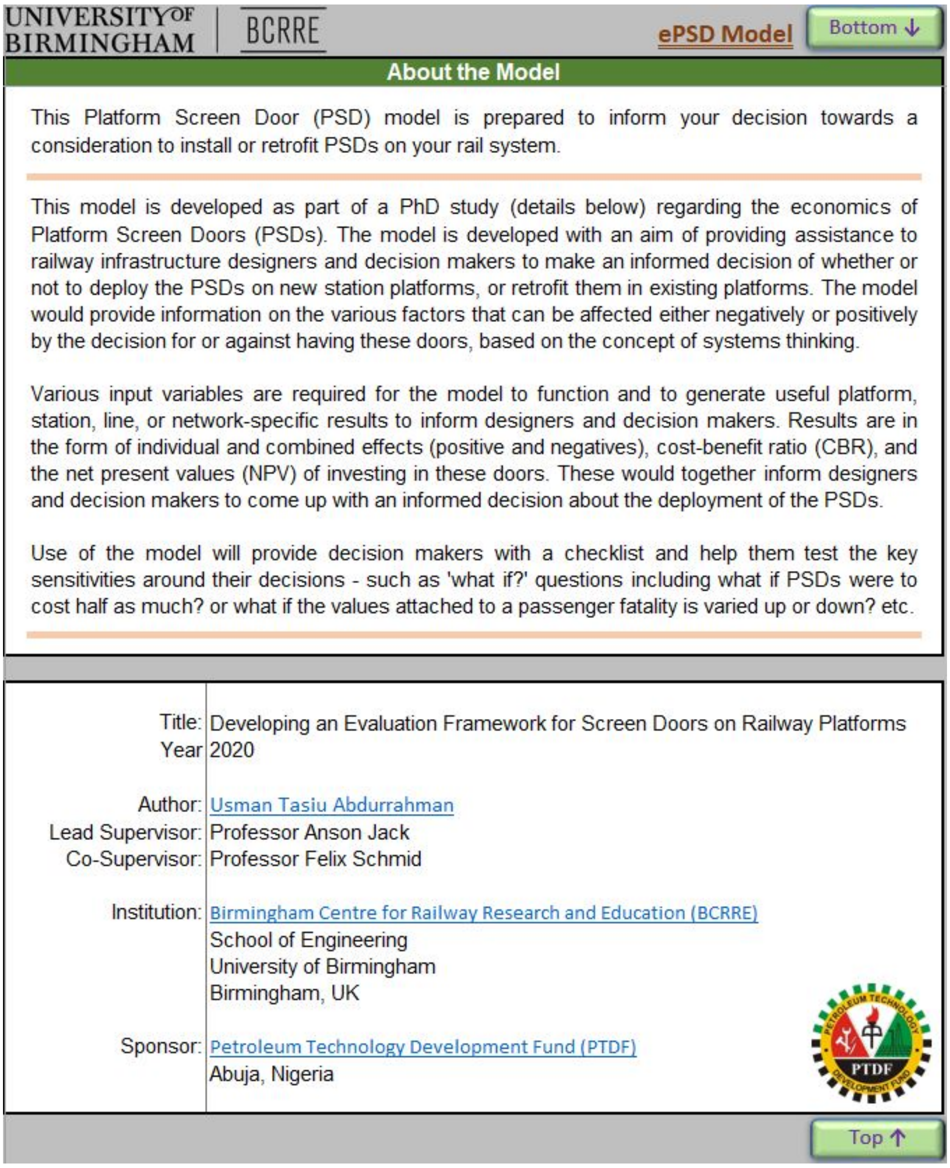

FIGURE F.1: Screenshot of the First Sheet Containing Information About the Model (Author)

ePSD Model

Key to all Sheets

S/N	Sheet	Content	Remark
1	About the Model	A brief explanation about what the model is, who it is built for, and what to expect from the results.	
2	Information Sheet	The present sheet, contains the general information about the model, what is contained in each sheet, etc.	
3	Glossary of Terms	Contains a list of various terms relevant to the model with their corresponding meanings. This includes abbreviations, arithmetic units, etc.	Please refer to the main thesis, for details of the mathematical equations used.
4	Input	Input sheet presents the opportunity to key in specific data required for the model to run. This can be carried out in the column titled *your Input*. The model is structured in such away that ***default values*** would be used in situations where you don't have a particular data. In which case, you may leave the cell empty in order for the default value to be used. *Default values* were estimated using real world information from sources including TfL, MTR, MRT, SMRT Corp, etc. to serve as benchmark values and be used where you are unsure of the data to use.	
5	Computation	A place where the arithmetic is carried out. Inputs are used in mathematcal equations to compute various results as can be seen on the sheet.	This sheet is where the user sees the influence of their specific inputs.
6	Summary of Results	Summarises the key results in the statistical present values. It displays the various benefits and disbenefits that could be derived based on the data input.	
7	Conclusion	Based on the results in the summary sheet, the conclusion presents the cost-benefit analysis results and suggests a logical advice with regard to the consideration of Platform Screen Doors under those particular conditions.	

FIGURE F.2: Screenshot of the Information about all Spreadsheets Contained in the Model (Author)

UNIVERSITY OF BIRMINGHAM | BCRRE

Dear User

This Platform Screen Door (PSD) model is prepared to inform your decision towards a consideration to install or retrofit PSDs on your rail system.

Instructions

Please read these instructions *carefully* before you start using this model.

The model is developed mainly for an assessment on a basis of a ***platform.*** As such, the data you're required to key-in in the input sheet must be an average data per platform. However, if you are assessing a particular station with multiple number of platforms; line of service comprising several stations; or a whole rail network, please do indicate the total number of platforms on the input sheet. In which case you are required to enter only a platform average value for **all** the parameters. For instance, the value for *Avg. platform suicides* should be an average value for all platforms; *Platform length* should be in *m/platform*; and so on.

Default values are provided for each factor. These are real data averages collected from various metro systems. You are however encouraged to yse your own data as much as feasible to increase the accuracy of results to your specific case.

The ***currency information panel*** on the *input* sheet is vital to the model. Please insert the required currency information before running the model.

FIGURE F.3: Screenshot of the Instructions to Users (Author)

Having used the characteristics of a hypothetical station as input (see Figure B.1), results were generated as summarised in the model and shown in Figure F.4. The last three rows before the NPV are the extra rows to include any additional factors that the user identified as being significant but are not captured in the model. There is a room for up to three parameters to be added without having to change the model.

These are the <u>summary of results</u> and are used for the generation of the conclusion and charts in the ***conclusion*** page. **ePSD Model**

S/N	Parameter	Unit	For an Average Platform	For all 2 Platforms	Indicators	
		Unit	Statistical Present Values	Statistical Present Values	Benefits	Disbenefits
1	Value of total safety record	£/yr	6,874,456	13,748,912	✓	
2	Value of fare revenue for lost customer hours	£/yr	99,764	199,528	✓	
3	Value of service disruption	£/yr	69,499	138,999	✓	
4	Value of change in capacity	£/yr	(5,565,858)	(11,131,716)		✓
5	Value of Overall Energy	£/yr	4,318,623	8,637,245	✓	
6	Value of air quality improvement	£/yr	30,470	60,941	✓	
7	Value of ambient platform noise	£/yr	936	1,871	✓	
8	Value of Staffing	£/yr	(530,829)	(1,061,658)		✓
9	Net cost of PSDs installation	£	(3,370,299)	(6,740,599)		✓
10	Net cost of PSDs maintenance	£/yr	(1,446,404)	(2,892,808)		✓
11	Net cost of PSDs half-life overhaul	£	(751,819)	(1,503,637)		✓
12	Net cost of taking the PSDs down at lifetime	£	(90,940)	(181,879)		✓
13	Net salvage value of PSDs	£	90,940	181,879	✓	
	Parameter 1	unit				
	Parameter 2	unit				
	Parameter 3	unit				
	Net Present Value →	**£**	<u>(271,461)</u>	<u>(542,922)</u>		✓

FIGURE F.4: Screenshot of the Results in Summary Produced Using the Default Values (Author)

These results were further used to generate the graphical charts for a platform and for the whole station (as a multiple of number of platforms). Figure F.5 is a screenshot from the model showing the two charts, percentage of user contribution and the key statistical results, namely overall benefit, overall cost, BCR and NPV.

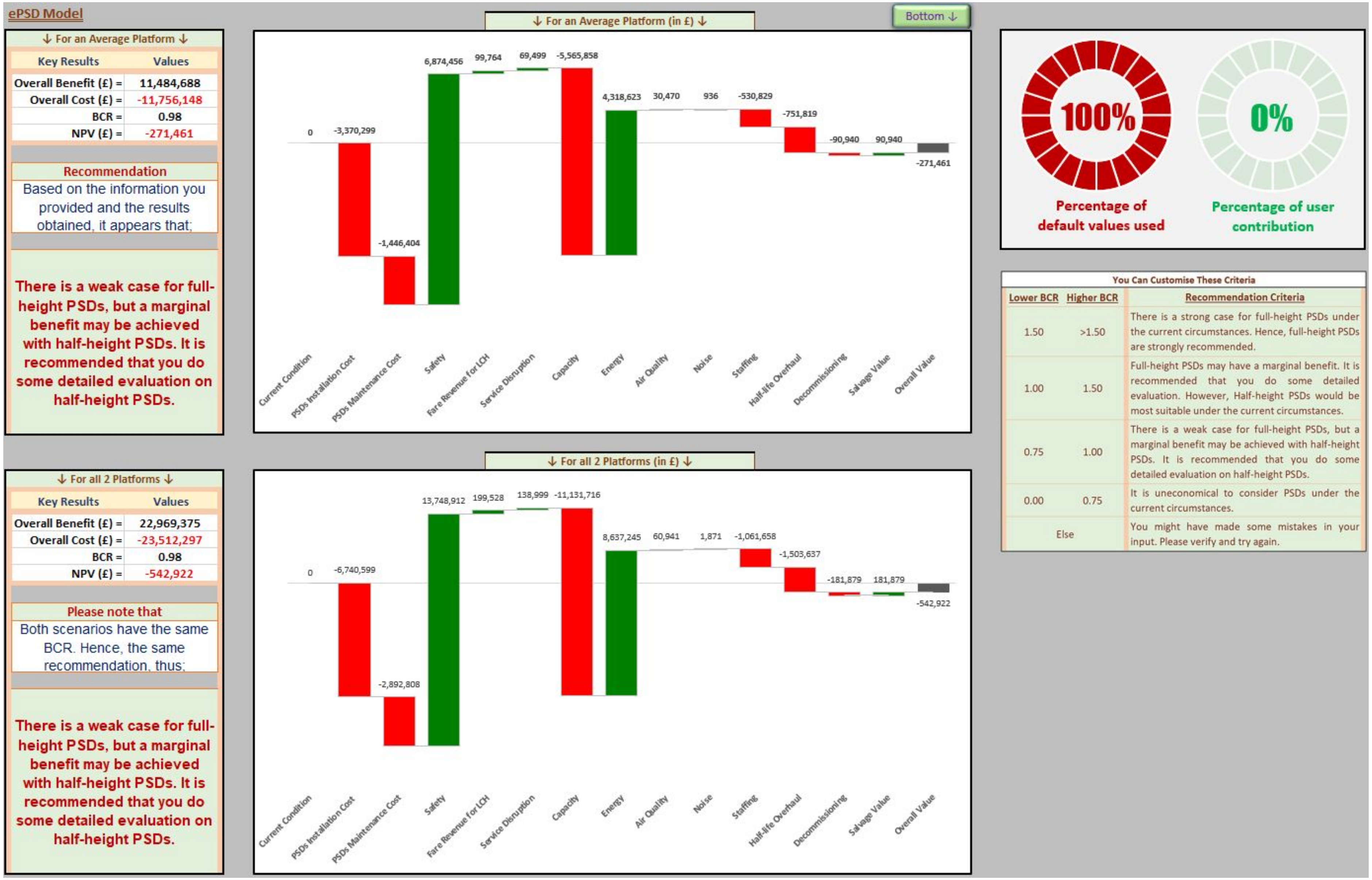

FIGURE F.5: Screenshot of the Last Sheet Showing Key Results (Author)

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