Structural Performance Model for Subway Networks

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ABSTRACT

Structural Performance Model for Subway Networks

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The *Transit Federal Administration* (FTA) reported that transit use increased by 25% between 1995 and 2005 in North America. Current communities are anticipating a high quality of life where people will be able to move freely with an affordable, reliable and efficient public transit. In 2009, the FTA estimated that 15.8 billion USD is needed annually to maintain and 21.6 billion USD is needed to improve the US transit network to satisfactory conditions. Moreover, the *Canadian Urban Transit Association* (CUTA) estimated that 140 Billion CAD are required for maintaining, rehabilitating and replacing the subway infrastructure between 2010 and 2014. It is apparent that subway management planning is of extreme importance in order to maintain the safety of infrastructure.

Subway management plans consist of assessing the structural performance of subway networks, predicting future performance, planning future maintenance and repair policies and optimizing budget allocation. Most transit authorities lack tools/models for assessing the structural performance of subway network. Therefore, the present research assists in developing the SUbway PERformance (SUPER) model, which assesses structural performance of different components in a subway network and develops performance curves of subway components, systems, lines and the entire network.

The developed SUPER model performs the following steps in order to achieve the above-mentioned objectives: (1) identifies and studies network hierarchy, (2) performs structural physical, functional and integrated performance assessment at the component level, and (3) constructs performance curves at the component, line and network levels. The SUPER model uses the Analytic Hierarchy Process and Multi-Attribute Utility Theory in order to assess the integrated components' performance. It also utilizes a reliability-based cumulative Weibull function to construct the performance curves of components. In addition, series/parallel system modeling techniques are adopted to evaluate and construct the performance models of the systems, lines and network. Finally, a software application based upon the SUPER model is developed, entitled the 'SUPER Model Software'.

Data are collected from the Société de Transport de Montréal (STM) inspection reports and through questionnaires. The questionnaires target transit authority managers and experienced structural engineers in both Canada and the USA. The developed SUPER model is applied to a network segment of the STM subway network. Results show that system deterioration rates are between 2% and 3% per year. The remaining useful service life are predicted to be until the year 2076 for renovated stations, 2030 for tunnels and between 2024 and 2040 for auxiliary structures. This research is relevant to industry practitioners (managers, engineers and field inspectors) and researchers since it develops structural performance assessment models and curves for subway networks.

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I dedicate this thesis to Metropolitan Ephraim Kyriakos of Tripoli and my wife Tereza, who both encouraged me to pursue this PhD degree.

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CHAPTER 1: INTRODUCTION

1.1 INTRODUCTION

Civil infrastructure is crucial for economic growth and prosperity. It is important to emphasize that a crisis situation exists in civil infrastructure, specifically public transportation infrastructure. According to McDonald (2005), “the reasons for the current crisis are well known. First, our public transportation infrastructure is aging. Second, our current system is not keeping up with the demands of a growing population. Third, public transportation is a critical component of our economic and social well-being.” The *Federal Transit Administration* (FTA) estimated that 15.8 Billion US Dollars are needed annually to maintain infrastructure conditions and 21.6 Billion US Dollars are needed to improve the status to good conditions (ASCE Report Card, 2009). The *American Society of Civil Engineers* (ASCE) Report Card (2009) assigned a grade of D (i.e., poor) for the transit infrastructure in the United States. Furthermore, according to the *Canadian Urban Transit Association* (CUTA), the transit infrastructure needs are reported to total 53.5 Billion Canadian Dollars in 2010 (CUTA, 2010).

Among the various civil public transportation infrastructure systems, subway networks represent a great challenge since they are the complex city’s essential mean of transportation. In the developed countries, such as Canada, large parts of subway system infrastructure have been in place for years. As a result, attention is now being focused on the Maintenance and Rehabilitation (M&R) of these existing facilities. As such, subway systems are subjected to a continuous increase in loading frequency and severity. They are also exposed to harsh environmental conditions, which increase deterioration rates to be higher than envisaged during the original design. The *Société de Transport de Montréal* (STM) needed an amount of 493 million CAD in 2007 in order to improve the subway system infrastructure. STM also estimated an amount of 5.1Billion CAD for its subway system infrastructure maintenance for the next ten years.

With the deteriorating condition of subway infrastructure and huge backlog of expenditures, public transit authorities have been under increasing pressure to develop strategies that manage the subway assets with a limited budget in a manner to ensure long term sustainable performance. It is no longer possible to only look at the deterioration of different structural components. Transit managers must have an overview of the complete/entire subway network performance. Hence, management of the subway network infrastructure has become a necessity, which is a complex and challenging task.

1.2 RESEARCH MOTIVATION AND PROBLEM STATEMENT

The research has been motivated by the serious lack of performance models for subway networks. This research encountered four main problems facing asset managers and researchers of transit authorities:

(i) Fast deterioration of existing subway networks: As shown in the abovementioned statistics and reports from Canada and the USA, it is quite clear that subway networks are severely deteriorating and in poor condition. Therefore, there is an urgent need for developing deterioration assessment tools and future performance prediction models for subway networks. These models can be used for the planning of future Maintenance and Repair (M&R) and optimization of budget allocation.

(ii) Limited scope of existing subway models: The existing subway models are few and show very limited scope. On one hand, a major existing research work assisted in developing a condition diagnostic model of solely subway station (Semaan, 2006). On the other hand, another existing research work helped in developing a life cycle costing model for a station slab (Farran, 2006). Neither model can be expanded for subway networks.

(iii) Inappropriate existing infrastructure mathematical deterioration models: Existing research works on deterioration modeling utilize techniques such as regression curves, Markov chains and reliability failure curves. These mathematical models cannot be applied to subway networks because they (a) require a huge amount of inspection reports, which are not available for subway networks; (b) entail high statistical analysis, which is intricate for a regular transit authority manager; (c) involve complex mathematical calculation and thus cannot be applied to a high number of structural components in a subway system; and (d) are difficult to use in order to evaluate network performance.

(iv) Lack of integration of condition and safety in a unique deterioration model: Existing research has developed models for either condition or safety. Combining condition and safety into one integrated model has yet to be researched/developed.

1.3 RESEARCH SCOPE AND OBJECTIVES

The present research focuses on assessing the performance of subway networks. The primary objective of this research work is to develop a structural performance model for subway networks which will be entitled: the "SUbway PERformance (SUPER) model". The new developed model has a key role in managing maintenance and rehabilitation (M&R) activities for subway networks. In order to fulfill this objective, the following sub-objectives are identified:

1. Develop a subway network hierarchy consisting of networks, lines, systems (stations, tunnels and auxiliary structures) and structural components.
2. Assess the performance of structural components (in each system) by integrating both physical (condition) and functional (safety) performance into one index.
3. Develop a performance model for components, systems, lines, subway network, and the entire subway network.
4. Develop an automated software or application for the developed performance model(s).

1.4 RESEARCH METHODOLOGY

The methodology utilized in this research consists of three different parts: the model development, data collection and model application to the STM data. The research methodology is illustrated in Figure 1.1.

1.4.1 The SUPER Model Development

The developed model comprises several steps as follows:

- **Network hierarchy identification**: A subway network hierarchy is identified. The complete subway network consists of different lines. Each line consists of different stations, tunnels and auxiliary structures, which are defined as systems. The systems are made up of several components. In addition, the station consists of slabs, walls and stairs at different floors. The tunnel consists of domes, walls and bottom slabs. The auxiliary structure consists of a top slab, bottom slab and side walls.
- **Performance assessment and modeling for components**: The SUPER model starts at the component level. The first step is to assess component performance. The SUPER model integrates the condition (physical performance) and safety (functional performance) of each component into a single performance measure, identified by the integrated performance index. It uses the Analytic Hierarchy Process (AHP) in order to evaluate weights of different condition and safety relevant structural cracks and defects. It also utilizes the Multi-Attribute Utility Theory (MAUT) in order to evaluate a physical performance index, a functional performance index and finally the integrated performance index of each component. The second step at the component level is the evaluation of a performance model that enables the development of a performance curve for each component.

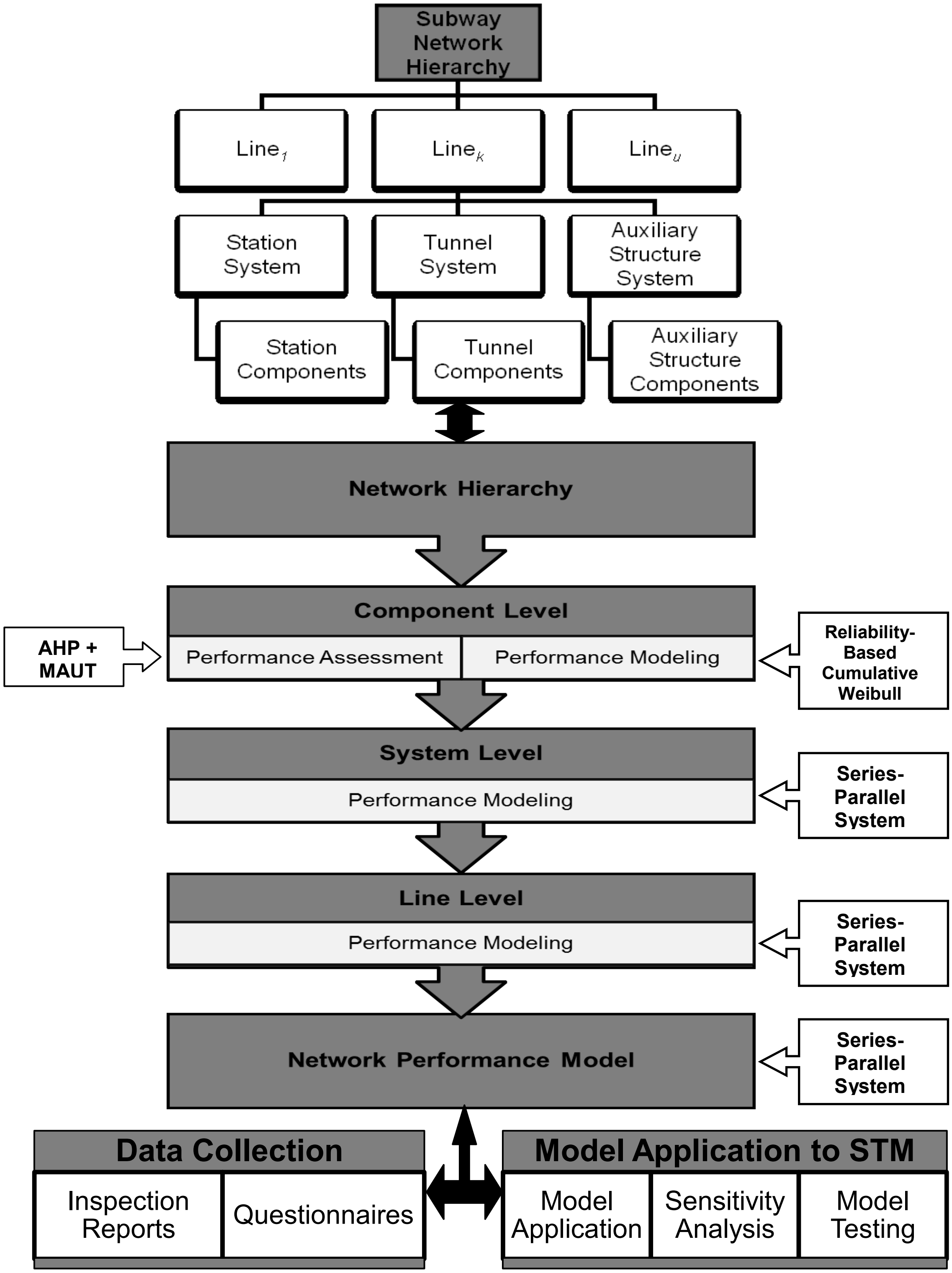


Figure 1.1 Research Methodology

An ideal (integrated) performance curve is constructed using a Weibull reliability-based cumulative function. Then, depending on the historical inspection reports, updates of the ideal curve are constructed. Finally, after the last inspection report, a predicted integrated curve is constructed for every component.

- **Performance modeling for systems**: The developed SUPER model evaluates the performance for various systems. Following the hierarchy, the subway systems' performances are developed for different stations, tunnels and auxiliary structures, using the series-parallel system reliability technique. A performance model is evaluated for each system independently.
- **Performance modeling for lines and network**: The line consists of several systems linked together; however, the network consists of different lines. The SUPER model evaluates line and network performance using the series-parallel system technique.

1.4.2 Data Collection

Data are collected through inspection reports and questionnaires collected from the STM and experts in subway networks in Canada and the USA. The inspection reports serve as one major part of the input for component performance curves. The data collected from questionnaires are used as input for the weights of structural cracks and defects.

1.4.3 The SUPER Model Application to STM

The SUPER model is applied to an STM network segment (i.e. a Sub-Network). This Sub-Network consists of three lines. The first line consists of nine systems: three stations, three tunnels and three auxiliary structures. The second line consists of six systems: two stations, two tunnels and two auxiliary structures. The third line consists of three systems: one station, one tunnel and one auxiliary structure. A sensitivity analysis is performed following the model application. The analysis evaluates uncertainties in (1) assessing the weights and scores of cracks and defects and (2) the effect of construction year on performance curves. Finally, the SUPER model is tested by comparing the predicted performance curves to the ideal ones.

1.5 THESIS OVERVIEW

The thesis is comprised of seven chapters. The first chapter introduces the thesis by presenting the research motivation, the objectives and a brief methodology. The second chapter consists of the literature review. This chapter is divided into the following major sections: i) review of the chief existing subway condition assessment and deterioration models; ii) expansion of the main infrastructure deterioration methodologies and models; iii) presentation of the major network performance models; iv) description of the Weibull analysis; v) overview of the main techniques used in the SUPER model such as the Analytic Hierarchy Process and the Multi-Attribute Utility Theory; and vi) presentation of the concrete structure degradation factors and cracks, and defects.

Chapter three presents the SUPER model methodology in more detail. This chapter is divided according to the steps involved in the SUPER model methodology. The first section of this chapter describes the subway network hierarchy. The second section illustrates the performance assessment and performance modeling of each component of the subway network systems. This is followed by an explanation of the subway system performance model. Sections four and five describe the subway line and network performance modeling respectively. Chapter four presents the data collection of the SUPER model. This chapter presents the data gathered from inspection reports and questionnaires and performs statistical analyses on some of these data. Chapter five illustrates both the results of the SUPER model implementation on a segment of the STM subway network. This chapter also presents the sensitivity analysis and ends with model testing. Chapter six describes the SUPER model software. The thesis ends with chapter seven which consists of the conclusions, contributions, limitations and future recommendations.

CHAPTER 2: LITERATURE REVIEW

As a result of aging, severe environmental conditions and deferred maintenance decisions, assets continuously deteriorate (Elhakeem, 2005). The ASCE Report Card (2009) assessed a grade of D (i.e. poor) for transit infrastructure in the USA. Decisions related to infrastructure maintenance and rehabilitation depend not only on an asset's current condition, but on their predicted deterioration behavior with time as well. It is important to present the existing relevant research in the literature dealing with: (i) subway assessment models, (ii) existing infrastructure deterioration methodologies and models, (iii) the main techniques used in the developed model and (iv) the causes, factors and defects of concrete structural deterioration. These items are presented in the following sections of this literature review.

2.1 EXISTING SUBWAY ASSESSMENT MODELS

2.1.1 Société de Transport de Montréal

2.1.1.1 Réno-Stations Programs

The Montréal subway, managed by the 'Société de Transport de Montréal' (STM), is considered to be one of the newest subway systems in North America. The first lines were built in 1966. Afterwards, lines were extended; hence new stations were built in 1976, 1987, 2001 and 2003, respectively. By 1990, the oldest stations were showing signs of deterioration and thus needed proper rehabilitation planning. In the 1990s, a program was implemented to renovate some of the old stations built in the 1960s. This program was called ‘Réno-Stations I’. Its main purpose was the structural and architectural renovation of oldest stations. In 2005, another program was implemented named ‘Réno-Station II’. It represents a continuation of ‘Réno-Station I’ and consists of the renovation of the remaining twenty-four (24) older stations built in the 1960s (Semaan, 2006). Under these two programs, the identification of structural deterioration was based on expert visual inspection. The inspector visually scores the condition based on a scale illustrated in Table 2.1.

Table 2.1 STM Visual Inspection Scale

Scale	Description
1	Critical Condition
2	Deficient Condition
3	Poor Condition
4	Acceptable Condition
5	Good Condition

Two sets of condition measures were identified by the visual inspection scale, the ‘Condition d’État de Matériel’ (CEM), and the ‘Condition d’État de Performance’ (CEP). The CEM corresponds to the physical condition of elements while the CEP corresponds to their performance condition. These two programs did not consider the full structural performance of stations as a whole. The worst CEM or CEP condition encountered in any element of the station was considered as representative of the whole station. Furthermore, the performance of the subway network is not considered.

2.1.1.2 The Subway Station Diagnosis Index Model

In 2006, a condition assessment model was developed by Semaan (2006), known as the Subway Station Diagnosis Index (SSDI). The SSDI model is used to diagnose a specific subway station and assess its condition using an index (0 to 10). Based on the SSDI model, the condition scale describes the station's condition state, its deterioration level (%) and proposed subsequent actions. The SSDI functional criteria are: (i) structural/architectural (global structure, global architecture, and concrete stairs); (ii) mechanical (mechanical stairs, pipes and mechanical equipment, ventilation system, and fire stand pipes); (iii) electrical (lighting, electric wires, and panels, transformers and breakers) and (iv) communication/security (alarm, smoke detectors, and communication system).

The SSDI model defines functional criteria and utilizes the 'Analytic Hierarchy Process' (AHP) in order to evaluate their weights. Then, the SSDI model uses the 'Preference Ranking Organization METHod of Enrichment Evaluation' (PROMETHEE) technique, developed by Brans and Mareschal (1986). The SSDI model compares the criteria value against two thresholds: a Critical Threshold (CT), a threshold above which the element criterion is considered dangerous or critical to public safety; and a Tolerance Threshold (TT), a threshold below which the element criterion is not considered dangerous but tolerable. The SSDI model outcome is a Station Diagnosis Index (SDI), evaluated using the Multi- Attribute Utility Theory (MAUT), which considers the global station level. The SDI condition scales is illustrated in Table 2.2.

Several limitations of the SSDI model are observed and can be defined as follows: (i) it is a diagnostic model and does not study the structural deterioration of the station over time; (ii) it is developed solely for stations, and cannot be adapted to tunnels and auxiliary structures; and (iii) it cannot be developed for the complete subway network.

Table 2.2 SSDI Model Condition Scale

SDI	Description	Deterioration Level *(%)*	Proposed Action
8 < SDI ≤ 10	*Good*	<17% Structural or, <12% Communications or, <15% Electrical or, <14% Mechanical	Long Term: * Expertise < 2 years * Physical < 5 years Review in 2 years
6 < SDI ≤ 8	*Medium*	>17% & <23% Structural or, >12% & <17% Communications or, >15% & <21% Electrical or, >14% & <21% Mechanical	Medium Term: * Expertise < 1 year * Physical < 2 years Review in 1 year
3 < SDI ≤ 6	*Deficient*	>23% & <35% Structural or, >17% & <26% Communications or, >21% & <33% Electrical or, >21% & <34% Mechanical	Short Term: *Expertise < 6 months *Physical < 1 year Review in 6 months
0 ≤ SDI ≤ 3	*Critical*	>41% Structural or, >30% Communications or, >38% Electrical or, >40% Mechanical	Immediate: Physical intervention Now

2.1.1.3 The Maintenance and Rehabilitation Planning for Public Infrastructure

In a parallel effort to develop a Maintenance and Rehabilitation (M&R) planning for the Montréal subway stations, Farran (2006) developed a 'Maintenance and Rehabilitation Planning for Public Infrastructure' (M&RPPI) model. The M&RPPI model is based on Life Cycle Cost Analysis for a specific element in an infrastructure. In evaluating the deterioration of the structural element, the M&RPPI uses Markov Chain (MC) theory. Transition Probability Matrices (TPM) are major inputs to the model. Then, both the actions (preventive, major repair and replacement) and respective costs are considered by the model. Afterwards, it utilizes Genetic Algorithm (GA) in order to optimize the Life Cycle Cost (LCC). The main objective of the M&RPPI model is to minimize the total LCC . Several important limitations are observed in the M&RPPI model are: (1) the M&RPPI application requires a huge amount of data input, (2) it only considers one element (i.e. metro station slab), and (3) the model cannot be used for subway networks.

2.1.2 Metropolitan Transit Authority of New York City Transit (MTA NYCT)

2.1.2.1 Point Allocation Model

The MTA NYCT was built in 1904. It is the largest transit authority in the eastern United States (Abu-Mallouh, 1999). In 1995, the MTA NYCT faced many problems with respect to some of its old stations, which forced it to re-evaluate the aging infrastructure and develop a ranking system for condition assessment. Each station is ranked in order of priority by allocating points to each of the considered factors depending on a rating system:

i. Structural conditions (up to 51 points).

ii. Daily usage (up to 25 points).

vi. Automatic Fare Control AFC (up to 2 points).

vii. Secured outside funding (up to 2

iii. Felonies (up to 2 points).

iv. Terminal station (up to 2 points).

v. Intermodal American Disabled Agreement ADA (up to 2 points).

points).

viii. Potential developer funding (up to 2 points).

ix. Point of interest (up to 2 points).

Points for each factor are added to each station in which the condition of a station assignment depends on total points (Abu-Mallouh, 1999). It is evident that the structural condition is the most dominant factor in this point allocation method. The point allocation model has many limitations, such as: (i) no deterioration level is described, (ii) no future prediction rating, and (iii) only applies to stations and not for subway network.

2.1.2.2 Model for Station Rehabilitation Planning

Abu-Mallouh (1999) improved the condition assessment point allocation model of the MTA NYCT and developed a 'Model for Station Rehabilitation Planning' (MSRP). The MSRP is mainly a budget allocation model that starts by assessing the condition based on functional and social factors and then allocates the budget of the stations. The MSRP considers functional factors (i.e. structural, mechanical, communications, water condition, and safety) and social factors (i.e. daily usage, safety, and level of service). MSRP uses the Analytic Hierarchy Process (AHP) to assign weights for each station and then, uses Integer Programming (IP) to optimize the fund allocation for rehabilitation. Stations that have a certain weight and budget above certain thresholds assigned by management are eligible for instant rehabilitation (Abu-Mallouh, 1999). The main limitations of the MSRP model are listed here:

- The MSRP ranks the stations and does not evaluate a condition or assess deterioration of the station.
- It assumes budget allocation for future years for a station depending on the current condition and not on a forecasted condition.
- It considers all the stations of MTA NYCT independently, thus it fails in evaluating the entire network.
- It considers a large number of factors, which renders it very lengthy to implement.
- It uses fictitious data without validation using real data.

2.1.3 California Train Transit (Cal Train)

The Cal Train transit network, inaugurated in 1864, is considered to be one of the oldest networks in the United States. In the 1990's Cal Train had set objectives to improve its stations. Therefore, in 1994 Cal train has developed a specific system for the evaluation of stations and ranking from *excellent* to *poor*: (1) Excellent; (2) Good; (3) Average; (4) Below average; (5) Poor. The criteria used for the evaluation of the stations are:

i. Ease of access to and from the station.

ii. Location of the station and proximity to amenities.

iii. Availability of parking capacities.

iv. Ability to use other modes of

vi. Physical and structural condition of the stations.

vii. Public information, signs, telephones.

viii. Ticket vending machines.

ix. Security.

transportation.

v. Appearance and cleanliness of the stations.

x. Safety.

The evaluation method adopted was a weighted average of the criteria values (Abu-Mallouh, 1999). The Cal Train evaluation method does not develop a deterioration model; however, it also fails to consider the subway network.

2.1.4 Paris Rapid Transit Authority (RATP)

In 1982, the *Régie Autonome des Transports Parisiens* (RATP) made a considerable effort to develop a selection procedure of the stations that should be renovated. A study was delegated to LAMSADE, University of Paris-Dauphine in France (Roy *et al.,* 1986). The study resulted in a selection procedure that used seven criteria:

i. Platform users.

ii. Transit passengers.

iii. Coordination of works.

iv. Maintenance of wall and roof tiles.

v. Visual aspect of the station.

vi. Level of discomfort.

vii. Environment (RATP wish to favor stations in rapidly changing and low-income areas).

LAMSADE used the ELECTRE III decision support model and software to rank the stations according to the criteria listed above (Roy *et al.*, 1986). The result of the study is a ranking model of the station and not a deterioration model of the subway network.

2.1.5 London Transit

In 1990, the primary objective of London Transport was to improve its stations. It developed the Key Performance Indicator (KPI), which evaluated the performance of the station from the point of view of its customers (Tolliver, 1996). Surveys and interviews were performed in order to obtain a direct evaluation of customer satisfaction. Customers were asked to rate 23 items on a scale from 0 to 10, based on the following criteria:

i. Cleanliness.

ii. Information services.

iii. Information on trains, station services (number of ticket gates, ease of access to platforms, buying a ticket and the degree of platform crowding).

iv. Safety and security.

v. Train services (crowding, journey time, smoothness of the ride…).

vi. Staff helpfulness and availability.

KPI is an overall weighted average of the 23 measures of evaluation based on user's satisfaction (Abu-Mallouh, 1999). The London Transit Key Performance Indicator method is not a deterioration model.

2.1.6 Summary

It can be concluded that most existing subway models do not have deterioration modeling as their scope. Hence, no deterioration models exist for subway stations, tunnels and auxiliary structures. Furthermore, no models exist for the entire subway network. The literature of the different existing deterioration methodologies is explored in the sections that follow. It is important to review the existing deterioration methodologies and study their applicability to subway systems and networks

2.2 INFRASTRUCTURE DETERIORATION METHODOLOGIES

Deterioration models are essential for asset management because they can predict the future deterioration of an asset or its components (Madanat 1993; Madanat *et al.,* 1997). Deterioration is by definition the gradual decrease in performance over time. Therefore, it can be understood as the opposite or inverse of performance. Thus, performance is generally understood as behavior related to use (Sarja and Vesikari, 1996). In principle the performance can be related to stability, safety, serviceability, integrity and other characteristics. Performance is always a function of time and is always measured 'over time' or 'with time'. When time is considered in the evaluation of performance, various external factors, called degradation factors, take on great significance. In this manner, performance is linked to the concept of degradation. On the other hand, service life is the period of time after construction during which the performance requirements are fulfilled (Sarja and Vesikari, 1996). Prediction of service life is an important and fundamental aspect of performance modeling. Service life is the period of time from the completion of the facility to when the facility or any of its components reaches a state where the facility cannot provide acceptable service because of physical deterioration, poor performance, functional obsolescence, or unacceptably high operating costs (Hudson et al. 1997).

Evaluation of overall service life of infrastructure assets should be based on the life of critical structural components. Service life can be estimated from: (1) empirical experience; (2) a historical database using survivor techniques; (3) established performance models; (4) laboratory testing; and (5) accelerated field testing (Hudson *et al.,* 1997). This section investigates the most important techniques used for modeling and predicting the deterioration, or inversely, the performance of infrastructure. Mathematical presentations that show decreased performance (or increased deterioration) as a function of time and appropriate design parameters are called performance models (Sarja and Vesikari, 1996). Performance modeling is an important part of infrastructure management on both project and network levels. A performance model relates a selected performance indicator to a set of causal variables such as age, load, load repetitions, usage history, material properties, environmental factors and M&R history (Hudson *et al.*, 1997).

According to Hudson *et al.* (1997), performance models can be developed by a variety of techniques, including the following: (i) an expert system incorporating a knowledge base of empirical experience, (ii) a regression analysis, (iii) Markov transition probabilities, (iv) artificial neural network analysis, (v) Bayesian methodology, and (vi) econometrics methods. Elhakkem (2005) defines three categories of evaluating major deterioration techniques: (1) deterministic, (2) stochastic, and (3) artificial intelligence models. Figure 2.1 illustrates the different techniques used in performance modeling by combining those of Hudson and Elhakkem.

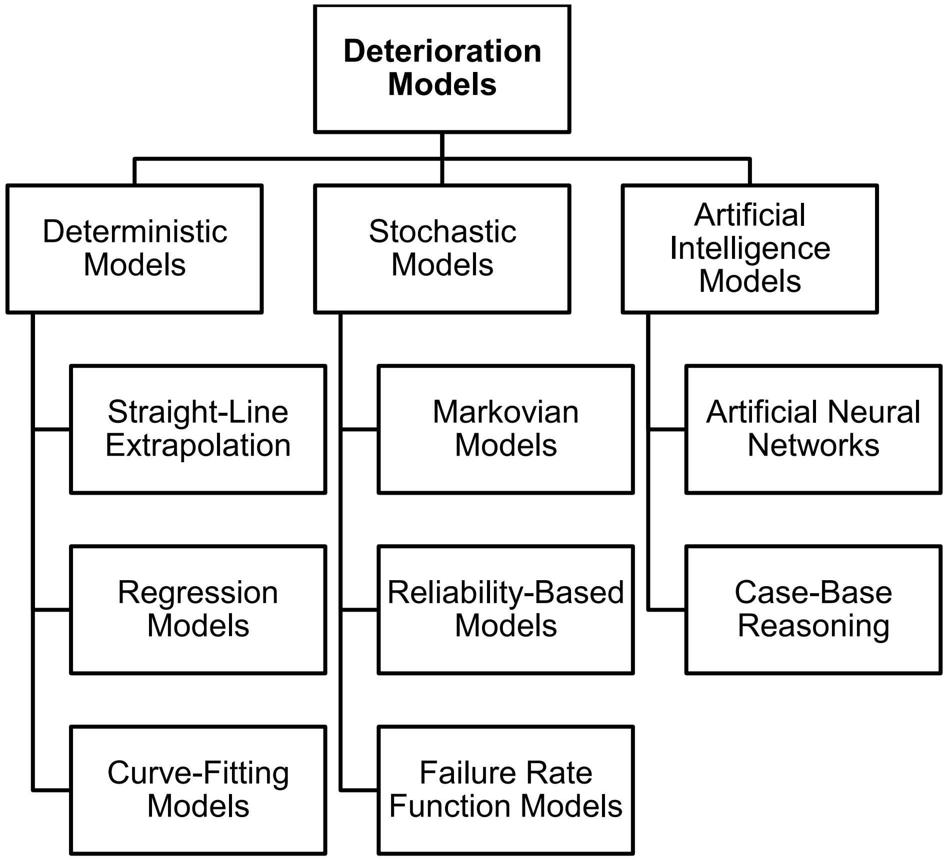


Figure 2.1 Deterioration Modeling Techniques

2.2.1 Deterministic Models

The deterministic models vary from simple straight-line extrapolation to regression analysis models.

2.2.1.1 Straight-Line Extrapolation Models

In the simple case, the model is established by stretching a line between two points with known conditions; it is possible to extrapolate the future condition at any time to a third point, as shown in Figure 2.2. The straight-line extrapolation models are too simplistic for the modeling of the probabilistic nature of failures. In addition, these models fail to relate the rate of deterioration with time. Hence the rate of deterioration and time are considered independent (Tran, 2007).

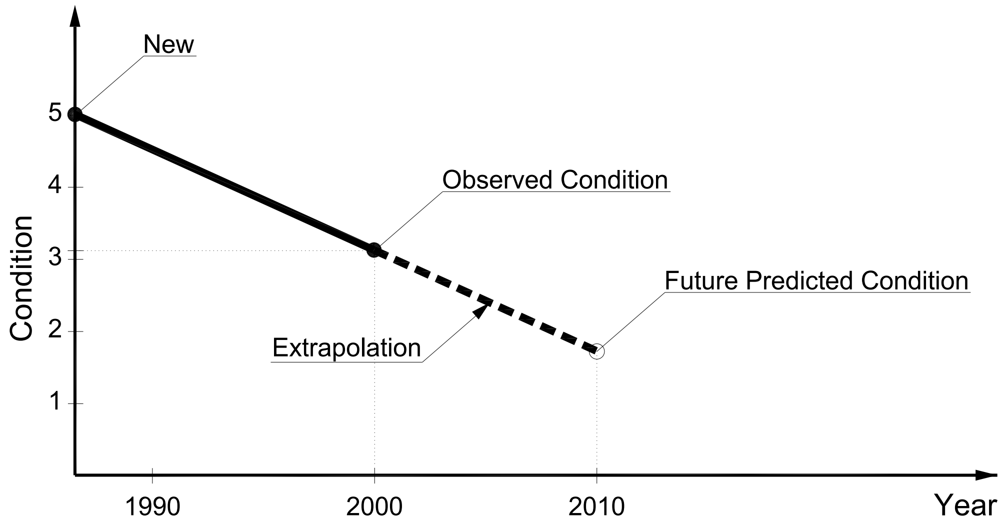


Figure 2.2 Straight-Line Extrapolation Deterioration Model

2.2.1.2 Regression Models

Regression analysis provides a more accurate representation of future deterioration than simple straight-line extrapolation. Regression is a statistical tool that can be used to investigate relationships between variables. There exist various types of regression analysis such as linear, non-linear, stepwise and multiple regression. The technique starts with assuming a suitable function that fits the available data. This can be done by using a scatter diagram. If, for example, the data seem to be fit by a line (y=a.x+b), then regression analysis tries to optimally determine the coefficients that represent that line (i.e. the slope, or the y-axis intercept). The process determines these coefficients based on minimizing the error between the predicted values and the actual ones as illustrated in Figure 2.3. Typical functions could be in the following forms:

$Y = a_0 + a_1.x$ Linear

$Y = a_0 + a_1.x + a_2.x^2 + \ldots + a_j.x^j$ Polynomial

$Y = a.\ x^b$ Exponential

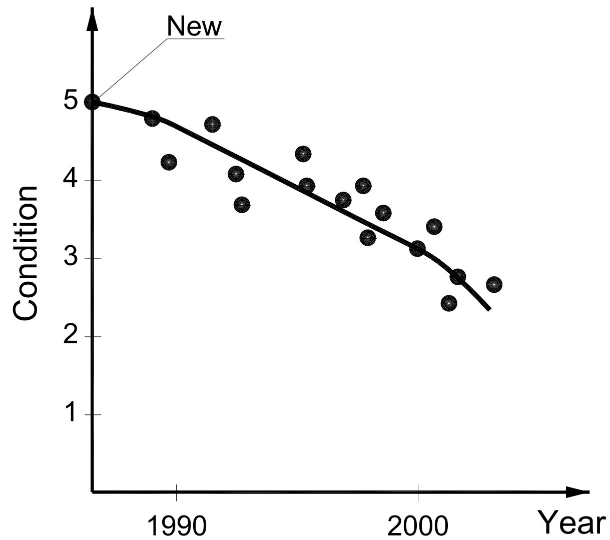


Figure 2.3 Regression Models

Various functions can be tried and the closest fit to the data can be selected to represent the relationship among the variables. This can be done by calculating the correlation coefficient (R^2) which ranges from 0 to 1, where closer to one represents a better correlation of the data. The main drawbacks of regression modeling are as follows:

i. Regression modeling has three major limitations: i) if the scatter diagram does not show a known model shape, ii) if many different independent variables influence the dependent variable, and iii) if the goodness of fit is low (low R^2 values) (Hudson *et al.,* 1997).

ii. Regression models fail to consider probabilistic behavior of deterioration, and assume that the deterioration rate is independent of time (Tran, 2007).

iii. According to Madanat and Ibrahim (1995) and Madanat *et al.*, (1997), it is not appropriate to model discrete condition states using regression models (especially the linear regression model).

iv. Furthermore, the fitting of multi-linear (polynomial) regression models is mathematically difficult to assess. Hence, the polynomial deterioration model is a hard task that requires significant computational effort.

2.2.2 Stochastic Models

2.2.2.1 Markov Chain Models

Markovian models are the most common stochastic techniques that have been used extensively in modeling the deterioration of infrastructure facilities (Elhakeem, 2005). Many research efforts are based on Markov Chains (MC), for instance Morcous (2006) used this model for Bridge Management Systems. Wirahadikusumah (1999) and Baik *et al.,* (2006) developed sewer management models using Markov Chain (MC) modeling. Butt *et al.,* (1987), Yang *et al.,* (2005), Ortiz-Garcia *et al.,* (2006), and Hong and Prozzi (2006) used it for pavement deterioration modeling.

Markov Chain (MC) modeling considers the deterioration profile of the infrastructure as a stochastic process that evolves with time into a probabilistic process. The stochastic process is represented by an indexed collection of random variables and it describes the deterioration degree or state at a particular point in the service life of the deteriorated element (Hillier and Lieberman, 2005). Markov Chain modeling is a stochastic process characterized by the Markovian property, or lack-of-memory property. This Markovian property means that the probability of any future state, given any past and present state, is independent of the past state and only depends upon the present state (Farran, 2006). These models use the Markov Decision Process (MDP) that predicts the deterioration of a component by defining discrete states and accumulating the probability of transition from one condition state to another over a multiple discrete time interval (Lounis *et al.,* 1998).

Transition probabilities are represented by a matrix of order (n x n) called the Transition Probability Matrix (TPM), where (n) is the number of possible condition states, as shown in Equation 2.1:

$$\text{TPM} = \begin{bmatrix} p_{1,1} & p_{1,2} & \dots & p_{1,n} \\ p_{2,1} & p_{2,2} & \dots & p_{2,n} \\ \dots & \dots & p_{i,j} & \dots \\ \dots & \dots & \dots & \dots \\ p_{n,1} & p_{n,2} & \dots & p_{n,n} \end{bmatrix} \tag{2.1}$$

Where 1, 2…n Condition States.

State *1* represents an excellent condition; state *2* represents a deteriorated condition and so on up to state *n* which represents the critical condition. Each element of the matrix $p_{i,j}$ represents the probability to move from state *i* to state *j* during a certain time interval called the transition period *'t'*. The sum of the probabilities in each row is unity. Since infrastructure deteriorates with time, the bottom triangle of the TPM is made of zero probabilities. Also reasonably assuming that deterioration happens gradually, the infrastructure component deteriorates only to the next state; hence two probabilities only appear on each row. As such the TPM can be re-evaluated as in Equation 2.2:

$$\text{TPM} = \begin{bmatrix} p_{1,1} & 1-p_{1,1} & 0 & 0 & ... & 0 \\ 0 & p_{2,2} & 1-p_{2,2} & 0 & ... & 0 \\ ... & ... & ... & ... & ... & ... \\ 0 & 0 & p_{i,j} & 1-p_{i,j} & ... & 0 \\ ... & ... & ... & ... & ... & ... \\ 0 & 0 & 0 & 0 & ... & 1 \end{bmatrix} \qquad (2.2)$$

Markov transition probability models are particularly useful where a historical database does not exist. They capture the experience of engineers or technologists in a structured way by utilizing different classes or combinations of situations and condition states (Hudson *et al.,* 1997).

Now, the Initial Probability matrix IP_0 is a row matrix as defined in Equation 2.3:

$$IP_0 = \begin{bmatrix} 1.0 & 0.0 & 0.0 & \ldots & 0.0 \end{bmatrix} \qquad (2.3)$$

The future condition vector 'FP_t' after '*t*' transition periods can be calculated as in Equation 2.4:

$$FP_t = IP_0 \,.\, TPM^t \qquad (2.4)$$

The single predicted condition state value 'ST_t' at any time '*t*' can be obtained using 'FP_t' and the vector of the possible states 'PS', as shown in Equation 2.5:

$$ST_t = FP_t \,.\, PS \qquad (2.5)$$

Where $PS = \begin{bmatrix} S_1 \\ S_2 \\ ... \\ S_n \end{bmatrix}$ *; and* S_n *= State n*

Or in another general form as in Equation 2.6:

$$[ST_t]_{1x1} = [IP_0]_{1xn} \cdot [TPM]^t_{nxn} \cdot [PS]_{nx1} \qquad (2.6)$$

For different times (t_i) used in Equation (2.6), it is possible to determine a relationship between condition and time. The Markov Chain approach captures the uncertainty in the deterioration process and evaluates the future condition based on the current condition. However, a few drawbacks of the Markov Chain Model must be considered:

- It assumes fixed transition probabilities, in addition to discrete transition time intervals, a constant population and stationary transition probabilities (Collins, 1972).
- For simplicity, it assumes that each state is independent. (DeStephano and Grivas 1998, Madanat *et al.,* 1997), thus past condition has no effect on predicted ones (Madanat *et al.,* 1997).
- The transition probabilities are estimated in terms of subjective engineering judgment and require frequent updating when new data are obtained (Tokdemin *et al.,* 2000).
- It does not predict the condition improvement after repair, i.e. maintenance done at a specific time (Madanat and Ibrahim, 1995).
- Finally, it is difficult to consider the interaction among different components (Sianipar and Adams, 1997) and therefore cannot consider network deterioration (Van Noortwijk and Frangopol, 2004a).

2.2.2.2 Reliability-Based Models

Reliability-based methods of modeling infrastructure' deterioration have gained increasing acceptance in academic circles. Reliability methods take a probabilistic approach that results in a reliability index or an inverse of the probability of failure. In structural assessment and design, critical factors such as the loads, resistances, and deterioration models are highly random. The associated uncertainties must be quantified in order to ensure the public safety (Estes and Frangopol, 2005). The reliability methods are computationally more difficult and complex than traditional deterministic methods. Reliability methods involve complex convolution integrals that have no closed form solution. Simplified methods use first and second order approximations in order to reduce the complexity of computation. Monte Carlo simulation is a crude method to solve the reliability problem, although it requires a large number of simulations to obtain good results. A reliability analysis begins with a limit-state equation or series of limit-state equations that govern the behavior of the structure. A structure is considered safe or reliable if its capacity (Resistance R) exceeds the demand (Load L) as in Equation 2.7:

$$\mathrm{R} > \mathrm{L} \qquad \text{or} \qquad \mathrm{R\text{-}L} > 0 \qquad \text{or} \qquad \frac{\mathrm{R}}{\mathrm{L}} > 1 \tag{2.7}$$

Now the probability that the structure performs safely (p_s) is the structural reliability, defined in Equation (2.8):

$$p_s = P(R - L > 0) = \iint_{R>L} f_{R,L}(r,l)drdl \tag{2.8}$$

Where $f_R(r)$, and $f_L(l)$ are the probability functions of R and L respectively, and $f_{R,L}(r,l)$ is their joint probability density function. The capacity R and the demand L may be functions of many other random variables. The generalized structural reliability problem may be formulated in terms of the random variables $X=\{X_1, X_2, X_3 ... X_n\}$ found in both R and L. A limit-state function $g(X) = 0$ describes the performance of the structural component in terms of the basic random variables X and defines the failure surface that separates the safe region from the failure region (Estes and Frangopol, 2005). So the probability of safety can be rewritten in the following Equation 2.9:

$$p_s = \int_{g(X)>0} fx(x)dx \tag{2.9}$$

Equation 2.9 represents the volume integral of $f_x(x)$ over the safe region $g(X)>0$. The solution to this integral is very complex, unless approximate methods are used. Approximate methods are the First-Order Reliability Method (FORM), and the Second-Order Reliability Method (SORM). In addition to these approximate methods, Monte Carlo simulation may be used. As a matter of fact, Monte Carlo simulation is a brute-force and intelligent way to avoid complex mathematical calculations. The probability of failure in this case is defined in Equation 2.10:

$$p_f = \frac{n_f}{n} \tag{2.10}$$

Where n *= Number of times a simulation is run,*

And, n_f *= Number of times* $g(X) < 0$.

The biggest drawback of Monte Carlo simulation is the large number of simulations required to obtain a valid result (Estes and Frangopol, 2005).

When attempting to make decisions about a structure over its useful life, time becomes an important variable. If the Load (L) and Resistance (R) of the structure can be projected for the future, the simplest approach is a point-in-time method in which the reliability is computed at various specific times in the future. A trend is established and the structure is scheduled for a repair when the reliability falls below an acceptable threshold level. The problems of this approach are: i) the difficulty of predicting the future load and resistance of the structure, and ii) the failure to account for previous structural performance. A better time-dependent reliability approach is to compute the probability that a structure will perform satisfactorily for a specific period of time. Thus, a survivor function S(t) is defined as the probability that an element is safe at any time t, as in Equation 2.11:

$$S(t) = P(T \geq t) = p_s(t) \qquad (2.11)$$

Where T represents time, and $t \geq 0$.

Some researches assume this survivor function in the shape of a cumulative Weibull distribution (Grussing *et al.,* 2006) or a Gamma distribution. One big advantage of reliability-based deterioration modeling is the flexibility of this method for the analysis of one component as well as a system of components. Many advantages are gained by quantifying the interrelationship between these components and by analyzing a structure as an entire system. A system analysis, for instance, may reveal that some repairs are more important than others. It also may reveal that while each individual component of a structure is safe, the whole system may be unsafe. There are two main types of systems:

series and parallel. A system is in series if the failure of any single component lead to the failure of the entire system. This type of system is called the 'weakest-link' system. In other terms, the system performs satisfactorily if and only if all the components perform satisfactorily (Hillier and Lieberman, 2004). Thus the series systems' (made up of n components) probability of safety is defined in Equation 2.12:

$$p_s = \prod_{i=1}^{n} p_{si} \tag{2.12}$$

And the respective probability of failure is defined in Equation (2.13):

$$p_f = 1 - \prod_{i=1}^{n} (1 - p_{fi}) \tag{2.13}$$

Now, a parallel system is defined to be a system that fails if all components fail; or alternatively, a system that performs satisfactorily if at least one of its components performs satisfactorily. Here all components operate simultaneously. A parallel system is often called a redundant system, i.e. there are alternative components existing in the system that help the system operate successfully or safely in case of failure of one or more components (Hillier and Lieberman, 2004). Thus the system in parallel (made up of n components) probability of safety is defined in Equation 2.14:

$$p_s = 1 - \prod_{i=1}^{n} (1 - p_{si}) \tag{2.14}$$

And the respective probability of failure defined in Equation 2.15:

$$p_f = \prod_{i=1}^{n} p_{fi} \tag{2.15}$$

A general structural system is usually made up of a combination of components in series and parallel. The most important drawback to reliability methods is the amount of input data needed to perform a valid analysis. Furthermore, the reliability results are only as good (or bad) as the input data that support them.

2.2.2.3 Failure Rate Functions Models

Failure rate functions representing deterioration are used since the 1960's. A failure rate function is defined as a lifetime distribution representing the uncertainty in the time of failure of a component or structure. The failure rate function *'r(t)'* relates the failure probability distribution *'f(t)'* to the failure cumulative probability distribution '*F(t)'* as defined in Equation 2.16:

$$\mathrm{r(t)} = \frac{f(t)}{1-F(t)} \tag{2.16}$$

A useful probabilistic interpretation of the failure rate function is that *r(t)dt* represents the probability that a component of age '*t'* will fail in the time interval *[t,t+dt]* (Van Noortwijk and Frangopol, 2004b). Failure rate increases as the deterioration increases over time. Failure rate functions are especially useful in mechanical and electrical engineering fields, where equipment assume two states: a functioning state and a failed state. On the other hand, a degrading structure can be in a range of states. Thus a serious disadvantage of failure rates is that they cannot be measured for structural components (Van Noortwijk and Frangopol, 2004b).

2.2.3 Summary

The above section explored the main techniques used in literature for the modeling of deterioration of infrastructure. It is important to investigate and review the main research models that used the above mentioned techniques in the field of infrastructure asset management.

2.3 INFRASTRUCTURE PERFORMANCE MODELS

There exist in the infrastructure literature several researches that utilize deterministic and stochastic deterioration modeling techniques. The main infrastructure fields are bridges, buildings, sewers and water mains. The main deterioration models expanded in the previous sections are used in order to develop several infrastructure models.

2.3.1 Bridges

2.3.1.1 PONTIS Bridge Management System

The Bridge Management System PONTIS (Golabi and Shepard, 1997; Thompson *et al.,* 1998) utilizes a Markovian deterioration model for bridges and pavement rehabilitation. For each component, PONTIS determines the optimal maintenance actions for which the expected discounted cost over an unbounded time horizon is minimal. Frangopol and Das (1999) and Frangopol *et al.,* (2001) showed that there are important limitations in this Markovian approach as follows: (i) the deterioration of a component is described in visual terms only; (ii) the condition deterioration is assumed to be a single step function; (iii) the future condition depends only on the current condition and not on the deterioration history; and (iv) the bridge system deterioration with regard to safety is not explicitly considered.

2.3.1.2 Reliability-Based Deterioration Profiles

Van Noortwijk and Frangopol (2004a), Frangopol and Neves (2004), Petcherdchoo *et al.,* (2006), Kong and Frangopol (2003), developed reliability-based deterioration profiles to be used for optimizing the maintenance of bridges. Their models consider the reliability (safety), the condition and the cost of maintenance without integrating them into one profile. The deterioration profiles for safety and condition are considered multi-linear and maintenance at specific time is represented as a jump in the profile as shown in the following Figure 2.4.

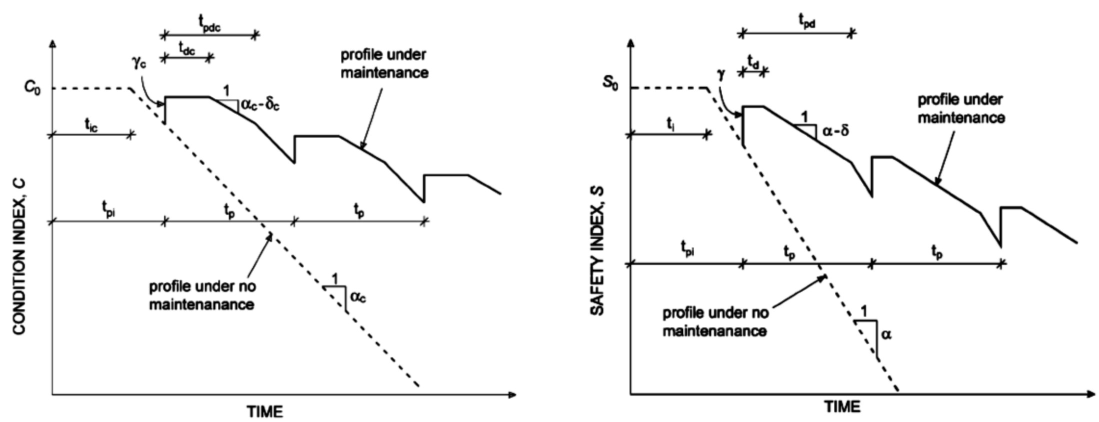


Figure 2.4 Reliability-Based Condition and Safety Profiles *(courtesy of Neves and Frangopol, 2004)*

The input to these deterioration models is considered probability distributions (Neves and Frangopol, 2004). However, the evaluation of these probability distributions is based solely on assumptions from one person, Mr. 'Denton', (Denton, 2002) through a personal communication in 2002 (Neves and

Frangopol, 2004). Although the reliability-based performance models consider reliability (safety) and condition (physical), it fails in integrating these two performance measures. Furthermore, the 'Frangopol' models assume the deterioration (both safety and condition) as linear only. In addition to the above, a significant weakness of reliability-based performance models developed until now is obtaining data, since they are all based on one expert opinion, that of Denton. Finally, all these models are not validated.

2.3.2 Buildings

Grussing *et al.,* (2006) developed a condition prediction model using the Weibull probability distribution. In their model, the cumulative probability distribution is used to construct the condition and reliability life cycle curve for building components. The Weibull statistical distribution represents the probability of time to failure of a component-section in service. It has natural boundary conditions:

- The curve starts at maximum performance (100);
- The curve ends at service life time;
- The curve approaches the minimum state (0) asymptotically.

Thus, the curve takes the shape of a classical deterioration curve. The resulting mathematical condition prediction model is shown in the following Equation 2.17:

$$C(t) = a \cdot e^{-(t/\beta)^{\alpha}} \qquad (2.17)$$

Where C(t) = Component condition index as a function of time,

t = time in years since the component is constructed,

e = exponential,

a = initial steady state component condition index parameter,

β = service life adjustment factor parameter,

α = accelerated deterioration factor.

Figure 2.5 illustrates an example of the cumulative Weibull function deterioration curve. The mathematical Weibull model has only three parameters to define. However, with the initial construction date, the expected service life date (usually assumed), and several inspections more than three data points exist on the curve. Thus, it is easy to calculate the function parameters. The model uses regression analysis in order to fit the prediction curve through the data points by minimizing the sum of squares of the residual error.

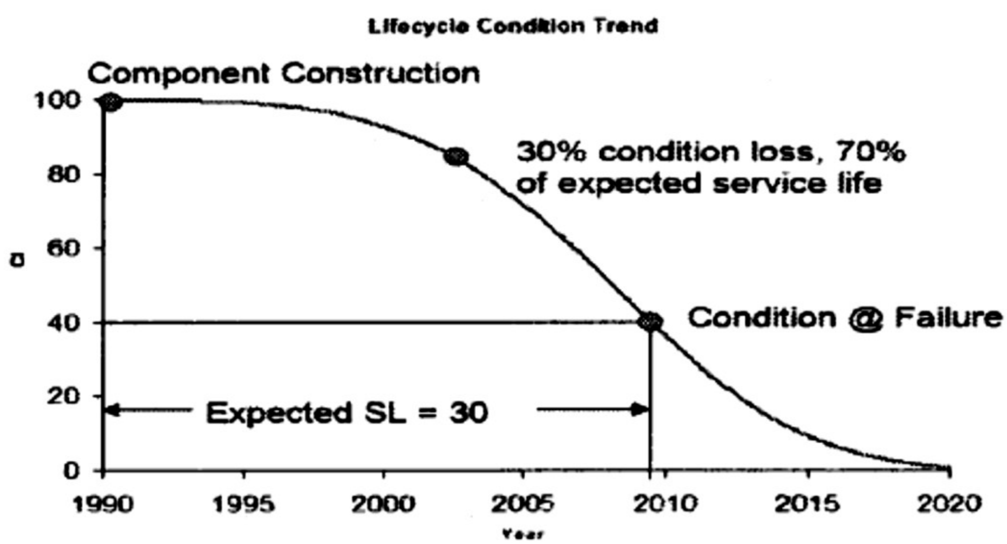


Figure 2.5 Weibull Deterioration Curve *(Courtesy of Grussing et al., 2006)*

2.3.3 Sewers and Water Mains

Chughtai and Zayed (2008) developed a condition prediction model for sewer pipelines. This model uses physical, operational and environmental factors. It utilizes multiple-regression modeling to come up with several prediction functions. Wang *et al.,* (2009) developed a deterioration model for water mains. This model uses physical, operational and environmental factors. It evaluates the deterioration using multiple-regression analysis.

2.4 NETWORK PERFORMANCE MODELS

Although a lot of existing performance models was developed by researchers for different components of infrastructure, few models addressed network performance. Furthermore, the existing network models were developed solely for bridges networks and pipelines networks. No research tackled networks of metro lines or subways, regardless of its importance. Network performance modeling techniques are characterized by two approaches: the system reliability approach and the transportation network optimization approach.

2.4.1 System Reliability Approach

The system approach technique was developed in terms of the reliability and safety of equipment. At a later date, it was applied to infrastructure (Cox and Tait, 1998). A 'system' is defined in the *Oxford English Dictionary* as "*a whole composed of parts in an orderly arrangement according to some scheme or plan*". Thus, the system can be treated as interacting or interdependent sets of components forming a network for the purpose of fulfilling some safety objective. Refer to 2.2.2 (stochastic models, reliability models), specifically equations (2.12) and (2.14) for the specific techniques of system reliability (i.e. the series system and the parallel system). Lalonde and Bergeron (2003), in their effort to develop a decision support methodology for asset management applied to pipelines, used the system reliability approach. Liu and Frangopol (2005) developed a bridge network reliability model using the system reliability approach. In their model, they considered the bridges acting as 'links' among the nodes of interest. The nodes of interest in highway networks could be cities hundreds of miles apart in a state-wide network and could be also shopping centers close to each other in a small regional network. The links (bridges) are the only possible failure components in the network.

2.4.2 Transportation Network Optimization Approach.

The origins of this approach come from *Graph Theory*, a branch of mathematics that evolved with Euler's formulation and solution of the famous Konigsberg bridge problem in 1736 (Liu, 2006). Traditional transportation network problems deal with network modeling and algorithms for the pure minimum cost flow problems, which can be further specialized as transportation assignment, shortest path and maximum flow problems in networks. Liu (2006) developed a bridge network model combining both the systems approach and the transportation network (the shortest path) approach.

2.5 WEIBULL ANALYSIS

Weibull analysis is the world's most popular method of analyzing and predicting failures and malfunctions of all types (Jardine and Tsang, 2006). The Weibull distribution is named after Waloddi Weibull (1887-1979), who found that the distribution of data related to product life can be modeled by a function of the following form defined in Equation 2.18:

$$f(t) = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1} e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}} \qquad \text{for } t > \gamma \tag{2.18}$$

Where β *= shape parameter, greater than zero,*

γ *= location parameter, greater than zero,*

η *= scale parameter*

and, t = time.

The cumulative Weibull distribution function (cdf) is defined in Equation 2.19:

$$F(t) = 1 - e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}} \tag{2.19}$$

Hence, the reliability function of a distribution is simply one minus the cumulative distribution function (cdf). The reliability function for the Weibull distribution is given by Equation 2.20:

$$R(t) = 1 - F(t) = e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}} \tag{2.20}$$

The key in plotting F(t) and R(t) is the estimation of the parameters β, γ, and η:

The shape β is often referred to as the slope of the cdf and R(t):

- For $0 < \beta < 1$, R(t) decreases sharply and monotonically and is convex.
- For $\beta = 1$, R(t) decreases monotonically but less sharply than $0 < \beta < 1$, and is convex.

- For $\beta > 1$, R(t) decreases as time 't' increases. The curve goes through an inflection point after this point, then decreases sharply.

The scale parameter η has the same effect on the cdf and R(t) as the abscissa scale (time). Thus, η has the same units as time. The location parameter γ, as the name implies, locates the distribution along the abscissa. Changing the value of γ has the effect of 'sliding' the cdf and R(t) either to the right ($\gamma > 0$), or to the left ($\gamma < 0$). When $\gamma=0$, the distribution starts at t=0 or at the origin. Finally, the estimation of the parameters of the Weibull distribution can be found graphically via probability plotting paper, or analytically, either using least squares or maximum likelihood.

2.6 THE ANALYTIC HIERARCHY PROCESS

The *Analytic Hierarchy Process* (AHP) is one of the methods used in prioritization modeling, importance weights evaluation or multi-criteria decision analysis. The AHP developed at the Wharton School of Business by Thomas Saaty (1980), allows decision makers to model a complex problem in a hierarchical structure. The hierarchy shows the relationships of the goal, criteria, sub-criteria, and alternatives as illustrated in Figure 2.6.

AHP allows for the application of data, experience, insight and intuition in a logical and thorough way. It enables decision-makers to derive rational scale priorities or weights as opposed to arbitrarily assigning them. In so doing, AHP not only supports decision-makers by enabling them to structure complexity and exercise judgment, but allows them to incorporate both objective and subjective considerations in the decision process. AHP is composed of several previously existing but un-associated concepts and techniques such as hierarchical structuring of complexity, pair-wise comparisons, redundant judgments, an eigenvector method for deriving weights and consistency considerations.

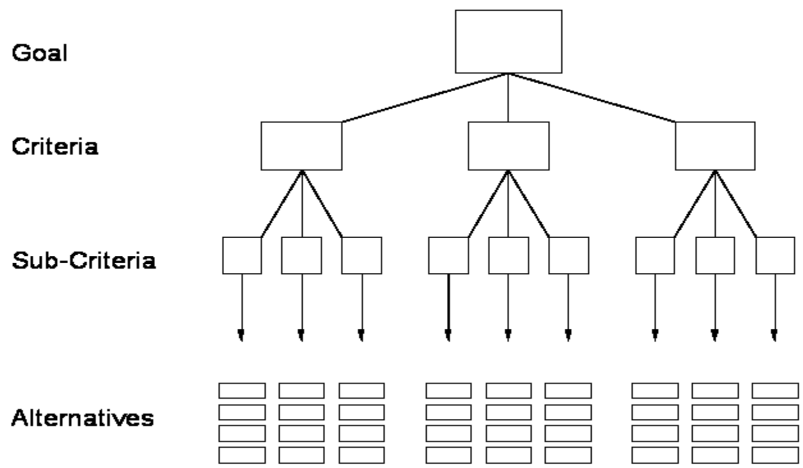


Figure 2.6 Decision Hierarchy

2.6.1 Mathematics of the AHP

The first step in the AHP is to arrange the decision-making problem in a hierarchical fashion. The next step is to establish priorities, (to perform pair-wise comparisons). Pair-wise comparisons of the sub-criteria and criteria (according to the hierarchy) are made in terms of one of the following:

- Importance: when comparing criteria with respect to their relative importance.
- Preference: when comparing the preference of criteria for alternatives with respect to an objective.

- Likelihood: when comparing uncertain events or scenarios with respect to the probability of their occurrence.

When comparing a pair of criteria, a ratio of relative importance, preference or likelihood of the criteria, based on a scale, can be established. Table 2.3 shows the original comparison scale developed by Saaty (1980).

Table 2.3 Saaty's Scale of Measurement

Value	**Definition**
1	Equally important or preferred
3	Slightly more important or preferred
5	Strongly more important or preferred
7	Very strongly more important or preferred
9	Extremely more important or preferred
2, 4, 6, 8	Intermediate values to reflect compromise

The comparison matrix is as shown in Figure 2.7 below (4x4 sample matrix).

$$\mathbf{A=}\quad \begin{array}{cc} & \begin{array}{cccc} \mathit{1} & \mathit{2} & \mathit{3} & \mathit{4} \end{array} \\ \begin{array}{c} \mathit{1} \\ \mathit{2} \\ \mathit{3} \\ \mathit{4} \end{array} & \left\{ \begin{array}{cccc} \mathbf{1} & a_{12} & a_{13} & a_{14} \\ 1/a_{12} & \mathbf{1} & a_{23} & a_{24} \\ 1/a_{13} & 1/a_{23} & \mathbf{1} & a_{34} \\ 1/a_{14} & 1/a_{24} & 1/a_{34} & \mathbf{1} \end{array} \right\} \end{array}$$

Figure 2.7 AHP Sample Matrix

Where A is the comparison matrix and a_{ij} is the pair-wise comparison scale.

Assuming that the comparison matrix is an *nxn* matrix A_{nxn}, hence the weight (W) is defined in Equation 2.21:

$$A.W = n.W \tag{2.21}$$

In evaluating W, the weight of each element is calculated. Furthermore, AHP allows for inconsistency, but provides a measure of the inconsistency in each set of judgments. Thomas Saaty, in 1982, derived formulae to measure the degree of inconsistency in order to control it. For a consistency matrix, $\lambda_{max} = n$, where λ_{max} is the largest eigen-value of the reciprocal matrix of order n. The Consistency Index can be calculated in Equation 2.22:

$$CI = (\lambda_{max} – n)/n-1 \tag{2.22}$$

And the Consistency Ratio, in Equation 2.23:

$$CR = CI / RCI \leq 10\% \tag{2.23}$$

The RCI (Random Consistency Index) refers to the average consistency for different order random matrices (Saaty 1982). A Consistency Ratio of CR ≤ 0.1 or 10% is an acceptable evaluation of the consistency of the judgment.

2.7 THE MULTI-ATTRIBUTE UTILITY THEORY

The *Multi Attribute Utility Theory* (MAUT) is one of the most widely used multi-criteria methods applied in prioritization modeling.

2.7.1 Principles of the MAUT

MAUT is based on developing a utility function representing the decision maker's system of preferences. The theory is founded on the following fundamental axiom: any decision maker attempts unconsciously (or implicitly) to maximize some function 'U' by aggregating all the different points of view which are taken into account. In other words, if the decision maker is asked about preferences, his answers will be coherent with a certain unknown function U, which has a general form of Equation 2.24:

$$U = U(C_1, C_2, \ldots, C_m) \quad (2.24)$$

Where m = total No. of alternatives, and C are the criteria involved in the decision-making problem.

The role of the researcher is to try to estimate that function by asking the decision maker some specific questions. Essentially two types of problems are studied in the frame of this theory:

1. What properties must the decision maker's preferences fulfill in order to be able to represent them by a function U with a given analytical from (additive, multiplicative, mixed, etc.)?
2. How can such functions be built and how can the parameters to be chosen in an analytical form be estimated?

2.7.2 The MAUT Common Functions

Generally, the utility function is either a non-linear or a linear function defined on the criteria space, such that:

$U(A_1) > U(A_2) \leftrightarrow A_1 > A_2$ (alternative A_1 is preferred to A_2)

$U(A_1) = U(A_2) \leftrightarrow A_1 = A_2$ (alternative A_1 is indifferent to A_2)

The simplest (and most commonly used) analytical form is the additive form, as shown in Equation 2.25:

$$U(A) = \sum_{i=1}^{n} u_i [C_i(A)] \tag{2.25}$$

Where n = total no. of criteria

Weights of criteria can also be included in the function, as in Equations 2.26 and 2.27:

$$U(A) = \sum_{i=1}^{n} W_i . u_i [C_i(A)] \tag{2.26}$$

$$U(A) = W_1.u_1 (C_1) + W_2.u_2 (C_2) + \ldots + W_n.u_n (C_n) \tag{2.27}$$

The u_i are strictly increasing real functions (their only purpose is to transform the criteria in order for them to follow the same scale: this avoids problems of units and ensures that the summation makes sense). The main assumption underlying the use of the additive utility function involves the mutual preferential independence condition of the evaluation criteria, described in Equation 2.28:

If $C_i(A) = C_i(B)$

$C_i(C) = C_i(D)$

And $C_i(A) = C_i(C)$

$C_i(B) = C_i(D)$

Then $U(A) - U(B) = U(C) - U(D)$ (2.28)

i.e. *A is preferred to B ↔ C is preferred to D.*

Where A, B, C, and D are various alternatives.

The global utility of the alternatives, estimated on the basis of the developed utility function, constitutes an index used for choice, ranking or classification purposes. This index can be represented on an ordinal scale (depending on the global utility). The weights included in the MAUT function can be evaluated using several tools, AHP for example. The additive model can be mathematically transformed into a multiplicative one, in Equations 2.29 and 2.30:

$$U'(A) = e^{U(A)} \tag{2.29}$$

Thus, $$U'(A) = \prod_{i=1}^{n} u'_i (C_i (A)) \tag{2.30}$$

The multiplicative utility function is efficient when a critical criterion dominates the decision.

2.8 DURABILITY OF CONCRETE

In order to study the structural performance of concrete, research must investigate the durability causes, factors and defects. Durability is defined as the "*capacity of a structure or a structural element to maintain minimum performance over at least a specified time under the influence of degradation factors*" (Sarja and Vesikari, 1996). While the degradation factors are defined as "*any of the group of external factors, including weathering, biological, stress, incompatibility and use, that adversely affect the performance of the materials and components*" (Sarja and Vesikari, 1996).

2.8.1 Degradation Factors

The different degradation factors causing the structural cracks and structural defects can be divided into two main groups: the factors affecting the degradation of concrete and those affecting the degradation of steel reinforcement (rebars). The concrete degradation factors can be divided into three main groups: structural, chemical and physical. Whereas the steel reinforcement degradation factors can be divided into two main groups: carbonation and corrosion, and chloride attack. The major degradation factors are defined as follows:

I. Concrete Degradation Factors

a. Structural

Design Deficiencies

The first and most important design factor is to reduce as much as possible the ingress of water by means of an efficient drainage system. The two remaining design factors are cover to reinforcement and environment. The cover provides the alkaline environment which protects the reinforcement against corrosion. Codes and standards generally give advice on the amount of cover to be provided according to the environment to which the concrete will be exposed during its normal working life. Last, but not least, the changes in allowable stress levels in steel and concrete over the years must be appreciated by the designer.

Construction Deficiencies

The major construction factor is related to concrete being too dry or too wet during casting. Honeycombing for example, can occur when the concrete is too dry, deliveries are too slow, in areas of heavy reinforcement congestion or when the formwork is not grout tight. Alternatively, if the concrete is too wet, the cement content is too low; or if contaminated materials are used, the low concrete strengths may lead to future durability problems.

b. Chemical

Sulphates Attack

Natural Sulphates (calcium, magnesium, sodium, and potassium), found in soils and groundwater, react with the tricalcium aluminate (C_3A) found in concrete to form gypsum. In due course, the gypsum is converted to ettringite which, having a higher volume than the original C_3A, causes expansion and disruption of the cement paste. There are three main types of failure due to sulphate attack. The first is the removal or softening of the cement matrix to produce an exposed-aggregate effect which is sometimes referred to as the acidic type of sulphate attack. The second type of failure is shelling of the concrete surface in successive layers, which is commonly referred to as an “onion-skinning” type of delamination. The third type of failure is associated with the aforementioned formation of ettringite, thaumasite, etc., which results in the overall expansion and cracking of the concrete.

Alkali-Aggregate Reactions (AAR)

The problem of Alkali-Aggregate Reactions (AAR) in concrete has been reported extensively over the years. Alkali-Silica Reaction (ASR) is the most common form of AAR and occurs when siliceous aggregates form a calcium alkali silicate gel. The ASR reaction will occur only when three conditions are met simultaneously. The reaction requires a sufficiently alkaline solution in the pore structure of the concrete, an aggregate susceptible to attack by this solution and a sufficient supply of water. If any one of the above three requirements is missing, the ASR reaction will not be initiated.

c. Physical

Freeze-Thaw Damage

The main concern here is with the problems encountered with hardened concrete due to the freeze-thaw cycle. Frost damage to concrete structures is generally confined to members exposed to freezing conditions while the concrete is still saturated with water. Repeated cycles of freezing and thawing of hardened concrete often result in surface scaling. This type of failure can be identified by the network of parallel cracks, spaced very closely together, which appear on the surface, often accompanied by lime leachate deposits (CBDG, 2002). Air-entraining agents, which form individual small air bubbles (less than 0.2mm in diameter), are generally used for concrete likely to be exposed to repeated cycles of freezing and thawing.

Shrinkage

Concrete is subject to volume change, including shrinkage stresses, during and after the hardening period. In practice, these deformations, due to volume change are subject to some measure of restraint resulting in the development of tensile stresses, which if excessive can cause cracking. Shrinkage due to moisture loss from either fresh or hardened concrete can take many forms, including drying shrinkage, plastic shrinkage, autogenous shrinkage and carbonation shrinkage. All of these modes of shrinkage can, under a sufficiently high level of restraint, cause tensile cracks to form in the concrete. Drying shrinkage can be a potential problem unless adequate curing is provided. Drying shrinkage is more likely to be encountered in thin walls and slabs in which restraint is provided by the reinforcement. The crack pattern is usually heavily influenced by the reinforcement and the cracks appear early in the life of the member. Plastic shrinkage cracking also occurs in slabs, normally within six hours of casting. Again, the crack orientation is influenced by the reinforcement providing the restraint.

II. Steel Reinforcement Degradation Factors

a. Carbonation and Corrosion of Reinforcement

In the case of reinforced concrete, the most commonly observed deterioration with time is corrosion of the reinforcing steel, which results in spalling of the cover concrete (Milne *et al.,* 2003). Carbonation occurs when carbon dioxide in the atmosphere dissolves in water in the concrete pores to form calcium carbonate. One of the main functions of the concrete cover is the prevention of carbonation. The rate of carbonation depends primarily on the amount of cover and the water to cement (w/c) ratio. Once carbonation has extended throughout the full depth of cover, corrosion of ordinary steel reinforcement is inevitable in an exposed environment. Initial cracking is observed to run along the line of reinforcement, followed by spalling due to the expansive nature of the rust formed. Crack patterns due to corrosion of the reinforcement are generally accompanied by rust staining.

b. Chlorides Attack

Chloride attack on concrete can take place from a wide variety of sources (CBDG, 2002), including the use of de-icing salts, exposure to a salty environment, impurities in the mixing water or aggregates, and the use of inappropriate additives, (i.e., calcium chloride, if used as an accelerator). The resistance of concrete to the ingress of chloride depends primarily on the permeability of the concrete and the ability of the cement paste to bind the chloride ions. The most significant effect is the reduction in the protective alkaline environment surrounding the reinforcement, leading in due course to the possible corrosion of the steel.

The concrete and rebar degradation factors, defined above, are illustrated in Figure 2.8.

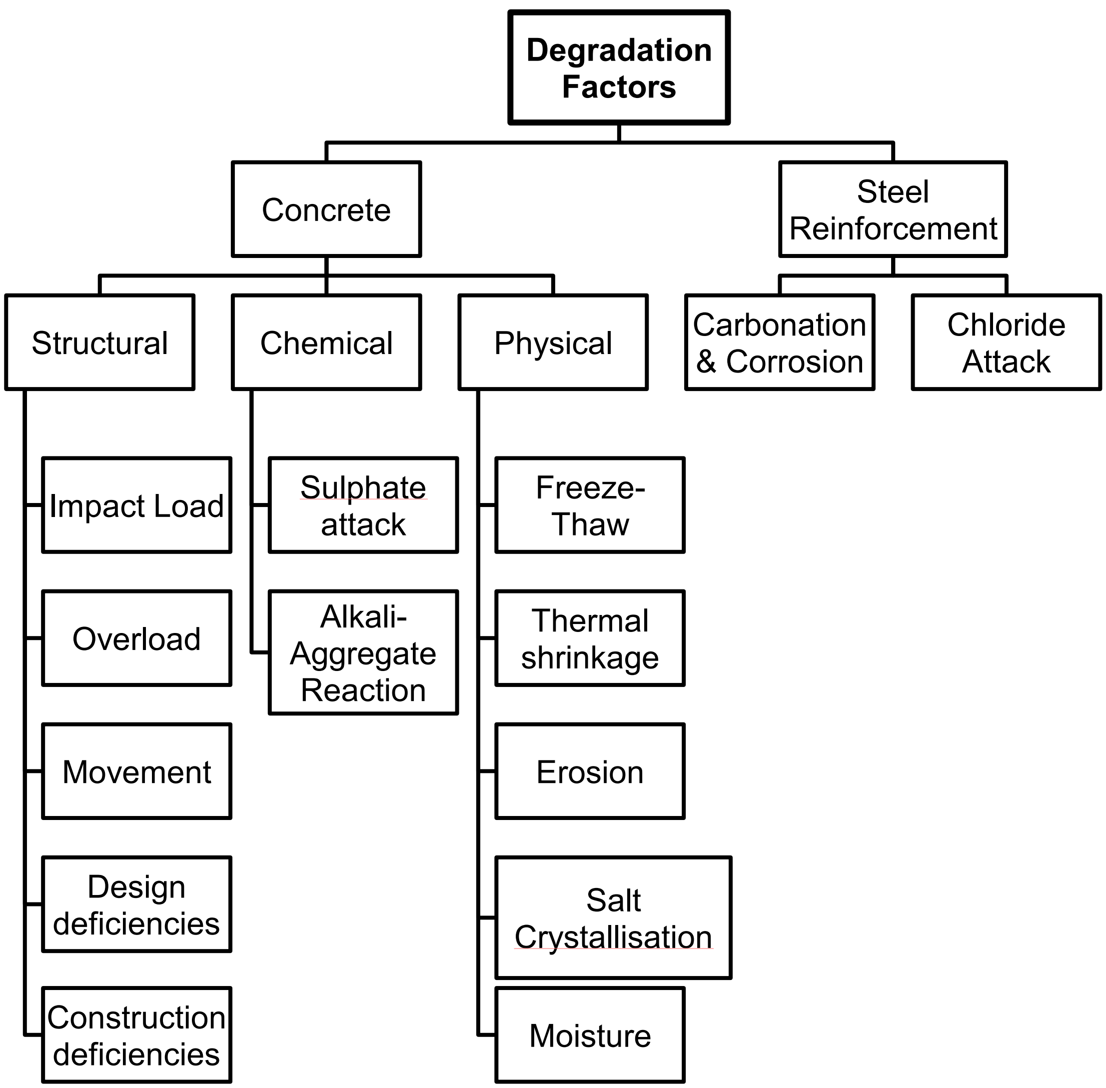


Figure 2.8 Concrete Degradation Factors

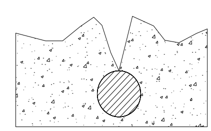
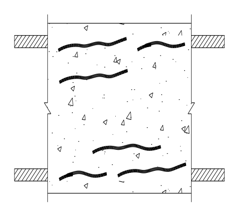
2.8.2 Durability Defects

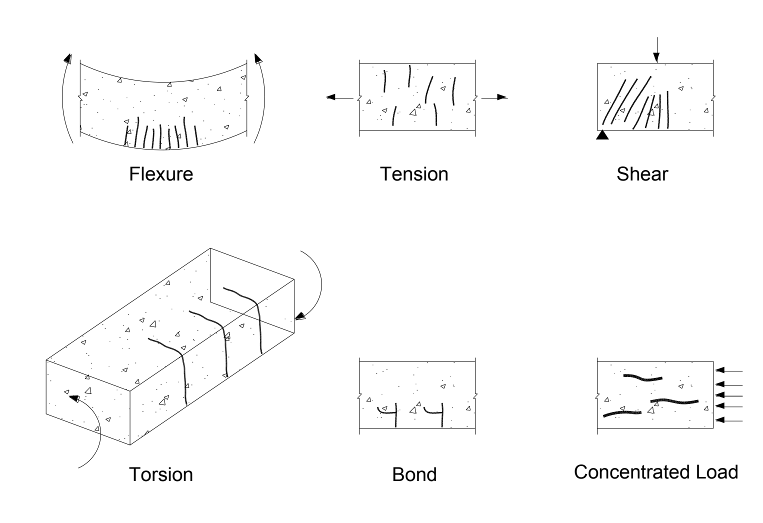
After reviewing the degradation factors affecting concrete durability, the research investigates the durability defects. Durability defects in concrete can be classified as structural cracks and structural defects (Mailvaganam *et al.,* 2000). Structural cracks are caused by the structural failure of the element, whereas structural defects are usually a symptom rather than a fault. In most cases, the latter defects do not lead to structural failure, but they can result in a definite loss of structural performance causing accelerated deterioration and reduced service life.

2.8.2.1 Structural Cracks

Table 2.4 summarizes the characteristics of structural cracks and lists the time periods in which they generally appear.

Table 2.4 Structural Cracks of Concrete

Cause	**Time of Formation**	**Manifestation**	**Shape**
Plastic settlement (slump cracking)	First few hours after casting	Cracks along lines of reinforcement. Cracks at changes in shape of section	
Corrosion	Not till after several months or years from construction	Cracking along lines of bars, developing into spalling.	

Loading in service	Depends on usage of structure	
Restraint	Depends on external influences	

It can be concluded that structural cracks can be caused by flexural, bond, torsional and shear failure. In addition, corrosion of steel, misalignment of joints, and movement of joints can be causes of structural cracks.

2.8.2.2 Structural Defects

Structural defects are mainly caused by induced moisture movement in addition to chemical attack. Descriptions of the some typically identifiable structural defects are summarized in Table 2.5 below.

Table 2.5 Structural Defects of Concrete

Defect Type	Description	Factors/Causes	Effect
1. Crazing	Cracking of the surface into small irregularly-shaped areas.	- Either shrinkage of the surface layer, or increase in volume of material below surface; - surface carbonates; - Concrete inadequately cured or excessively floated.	Does not affect structural integrity.
2. Corner cracks	Occur at the corners of doors and windows and other openings.	n/a	Does not affect structural integrity.

3. Corrosion cracks	Occur when the corrosion causes an increase in volume.	Carbonation and corrosion of steel reinforcement.	Progression of corrosion cracks results in spalling of wedge-shaped chunks of concrete.
4. Scaling	- Sloughing of mortar concrete; - cracks very fine and shallow; - occur mostly in young concrete.	- Chloride attack; - Freeze-Thaw action in the presence of salt.	May lead to structural damage.
5. Spalling	- Breaking away of a chunk or an area of the concrete on the surface; - cracks are long, wide, and deep; - occur mostly in aged concrete.	- Structural damage: Impact Load; - or from steel corrosion; - Presence of salts.	Affect steel reinforcement.
6. Pop-outs	Localized spalls	- Expansion of aggregate particles; - Moisture.	Does not affect structural integrity.
7. Dusting	Surface becomes soft and rubs softly as a fine powder.	- Concrete mixture too wet; - inadequate curing; - carbonation	Surface blemishes. Does not affect structural integrity.
8. Efflorescence	White deposits and stain due to migration of moisture salt from interior to exterior surface.	Excessive moisture ingress due to faulty detailing and poor concrete quality.	- Surface blemishes. Does not affect structural integrity. - Harmless superficial discoloration.
9. Weathering	Irregular discoloration.	Deposition of foreign matter or by an external/internal chemical reaction	Surface blemishes. Does not affect structural integrity.
10. Honeycombing	Irregular voids in the surface.	Concrete mix is under-sanded and/or placing conditions and techniques are poor.	Surface blemishes. Does not affect structural integrity.
11. Blow holes	Regular or irregular individual cavities.	n/a	

12. Sand-textured areas	Areas devoid of cement form.	n/a	
13. Scouring or sand streaking	Irregular eroded areas with exposed aggregate or sand particles.	Caused by drastic increase in the rate of bleeding.	
14. Cold joints	Joint cracks.	Concrete stiffens prior to placement of a subsequent mix.	
15. Form scabbing	n/a	Forms are stripped too early.	
16. Form streaking	n/a	Mortar leaking at form joints.	
17. Discoloration	n/a	Over-vibration.	

2.9 SUMMARY

The literature review has shown that previous research on transit subway networks lack sound structural performance models. On the other hand, deterioration models are developed for other types of infrastructure, such as bridges, buildings, sewers and water mains. The methods used to model deterioration are either deterministic, such as regression analysis or stochastic methods, such as Markovian models, reliability-based models or failure-rate functions analysis. Reliability-based models may take linear forms or Weibull cumulative function shapes. These existing methods show considerable limitations. Markov Chain, for example, assumes fixed transition probabilities, in addition to discrete transition time intervals, a constant population, and stationary transition probabilities. This method also assumes, for simplicity, that the states are independent, thus past condition has no effect on predicted ones. In addition, the transition probabilities are estimated in terms of subjective engineering judgment and require frequent updating when new data are obtained. Furthermore, Markov Chain does not predict the condition improvement after repair, i.e. maintenance done at a specific time. Finally, it is difficult to consider the interaction among different components using Markov Chain, i.e. network deterioration cannot be considered. On the other hand, reliability-based deterioration modeling is more flexible in analyzing one component as well as a system of components. However, the most important drawback to reliability methods is the amount of input data needed to perform a valid analysis. Furthermore, the reliability results are only good or bad as the input data that support them. Deterministic models such as regression models fail to consider probabilistic behavior of deterioration and assume that deterioration rate is independent of time. Furthermore, the fitting of multi-linear (polynomial) regression models is mathematically difficult to assess. Hence, the polynomial deterioration model is a time-consuming task that requires a great deal of calculation, which is data hungry technique.

CHAPTER 3: THE SUBWAY PERFORMANCE (SUPER) MODEL METHODOLOGY

3.1 INTRODUCTION

Subway network has the following two important characteristics:

1) Subway systems are complex systems that comprised of a big number of interconnected components. These components have different structural behavior.
2) Inspection of subway networks is an expensive task. It is noted that few inspections are done in the long history of subways.

Taking these two characteristics into account, the existing deterioration models investigated in the literature review cannot be applied to subway networks, for the following reasons:

i. Markov Chain theory is a '*Data Hungry*' technique. It requires a significant amount of data in order to evaluate the Transition Probability Matrices (TPM). This amount of data cannot be found in the subway networks history of inspections.
ii. Irregularities of M&R in the subway network make it very hard to develop the TPM.
iii. The large number and differences of structural components in the subway network make it hard for Markov Chain models to be developed for each component.

iv. Transit authority managers find it very difficult to apply statistical analysis in order to evaluate the TPM.
v. Due to the large number of structural components (each one has a different behavior) in a subway network, it is mathematically time consuming and hard to evaluate regression curves (either linear or polynomial) for subway components.
vi. Due to the small number of inspection reports, it is difficult to apply reliability models for subway network.
vii. It is very complex to apply markov chain models, regression models and reliability models in order to evaluate the deterioration of the combination of different components in a station or tunnel and even different stations and tunnels in one line.

Due to these limitations, it is apparent that a new deterioration (or performance) model should be developed, that takes into account the particularity and complexity of subway networks and the scarcity of inspection reports. The developed performance model, requires less data, is easy to construct and can be easily evaluated by transit authority managers. This developed model is entitled the SUbway PERformance (SUPER) model.

3.2 SUPER MODEL OUTLINE

The SUbway PERformance (SUPER) model methodology is outlined in Figure 3.1. The SUPER model development passes through the following main steps:

1. Identify a network hierarchy.

2. Components Performance Assessment and Modeling:
   a. Using the inspection reports, the different cracks and defects scores for each component are evaluated. Second, using the Analytic Hierarchy Process (AHP) technique, the different cracks and defects weights are evaluated. Third, using the Multi-Attribute Utility Theory (MAUT) technique, both the physical performance index and the functional performance index are evaluated. Finally combining these two indices using the Multi-Attribute Utility Theory (MAUT) technique, the integrated performance index is evaluated.
   b. Using the reliability-based Weibull cumulative function, the ideal performance model is constructed for each component. This ideal model is updated using the integrated performance indices already evaluated. Finally, the predicted performance model is developed, which refers to the final updated performance model.
3. Using parallel-series system modeling techniques, performance models for the different stations, tunnels and auxiliary structures of the subway network are developed.
4. Using parallel-series systems modeling techniques, performance models for the different lines of the subway network are developed.
5. Using parallel-series systems modeling techniques, a performance model for the complete subway network is developed.

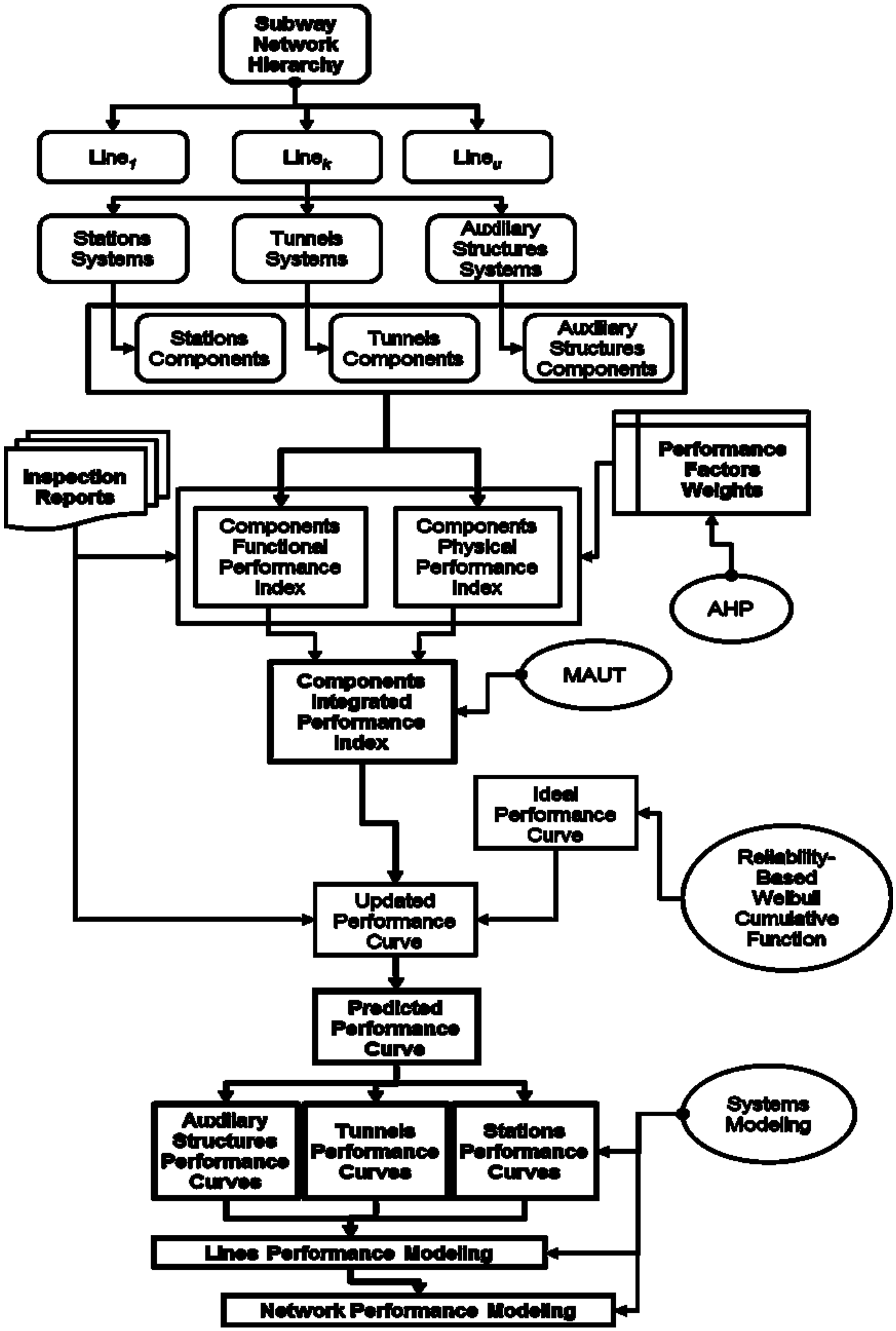


Figure 3.1 SUPER Model Outline

3.3 SUPER MODEL NETWORK HIERARCHY

The SUPER model starts by identifying the subway network hierarchy as illustrated in Figure 3.2. A subway network is composed of several lines ($line_1$... $line_k$, $line_u$). Each line is composed of several systems. The systems include the different stations, tunnels and auxiliary structures, which are linked together in order to form one line. Finally, each system is composed of different components. The network hierarchy is essential for the development of both performance assessment and models. In the following sections, the major components for each type of systems are defined and explained.

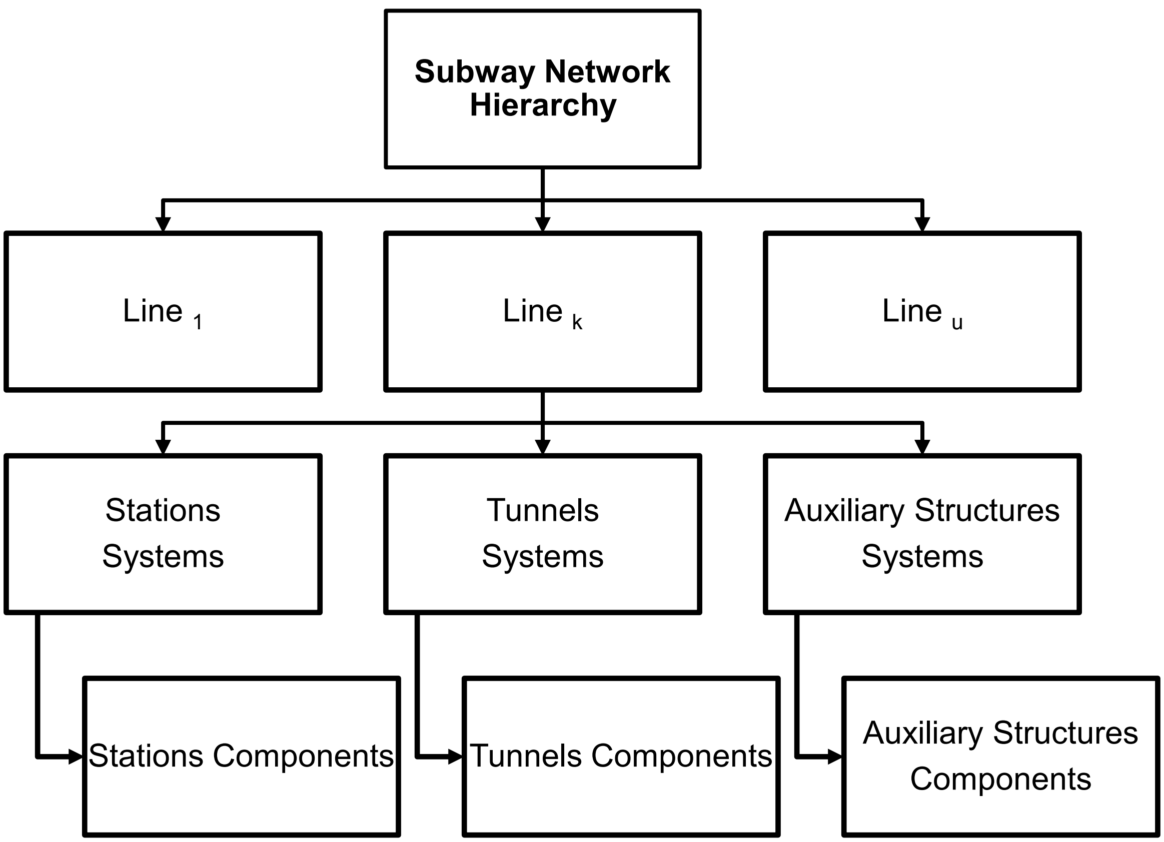


Figure 3.2 SUPER Model Network Hierarchy

3.3.1 Station System Hierarchy

Any generic station is made up of the following components: (i) exterior and interior walls (including columns), (ii) exterior and interior slabs (including beams), and (iii) exterior and interior stairs. These components form the station system and are illustrated in Figure 3.3.

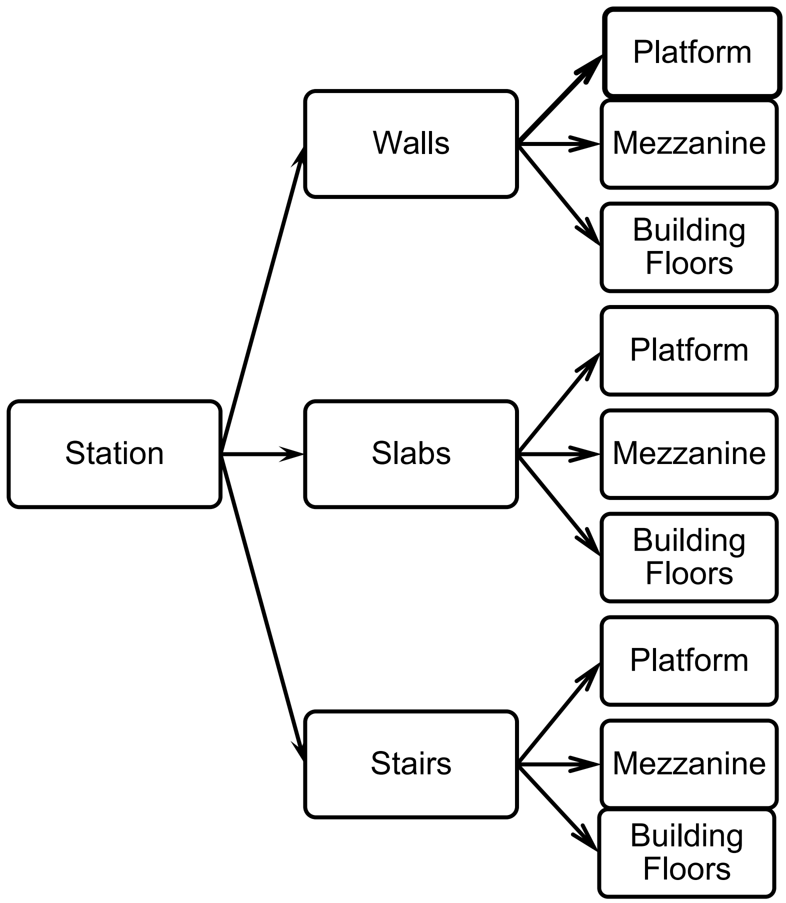


Figure 3.3 SUPER Model Station Hierarchy

3.3.2 Tunnel System Hierarchy

A typical tunnel is made up of the following components: (i) dome, (ii) side walls, and (iii) bottom slab. These components form the tunnel system and are illustrated in Figure 3.4.

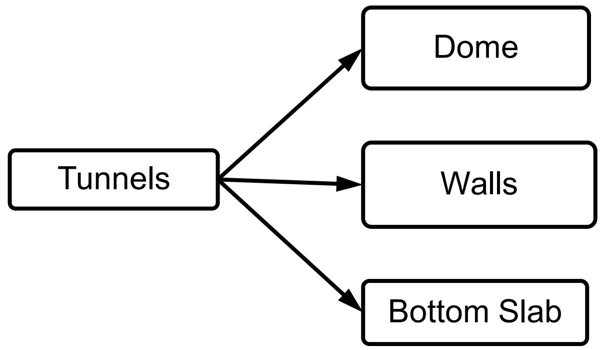


Figure 3.4 SUPER Model Tunnel Hierarchy

3.3.3 Auxiliary Structure System Hierarchy

Auxiliary structures are mainly ventilation and dewatering wells, mechanical ducting, and piping big openings. They could be located inside a station, or adjacent to a tunnel section, or at the end of a line. A typical auxiliary structure consists of two major components: (i) walls and (ii) slabs. These components form the auxiliary structure system and are illustrated in Figure 3.5.

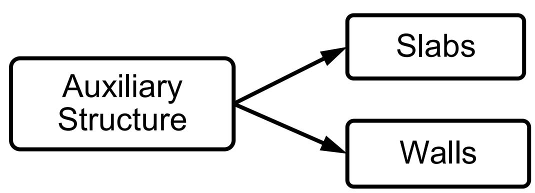


Figure 3.5 SUPER Model Auxiliary Structure Hierarchy

3.4 COMPONENTS PERFORMANCE ASSESSMENT

The *American Society of Testing Materials* (ASTM) international defines the structural component performance as the in-service functioning of the component for a specified use (ASTM E1480-92R04). The term refers to how effectively, safely and efficiently a structural component performs its mission at any time during its service life. A structural component performance state, which changes during time in service, is reflected by two different indicators: the “physical condition state”, and the “functionality state”. The “physical condition state” relates to a component’s general ‘physical fitness’, independent of its mission, as it deteriorates due to routine aging, excessive or abusive use or poor maintenance. The “functionality state” relates to the component suitability to function as intended and required for the mission. The “functionality state” is distinct from, and determined independently from the “physical condition state”. Therefore, the model defines the “physical condition state” indicator as the “Physical Performance” index (P_P), and similarly, the “functionality state” indicator as the “Functional Performance” index (P_F). Most of transit authorities and structural inspectors use these two indices independently. Using them independently implies two main disadvantages: (i) they do not reflect an integrated performance measure or index and (ii) they do not reflect the total performance change over time. The components’ performance assessment is outlined in Figure 3.6.

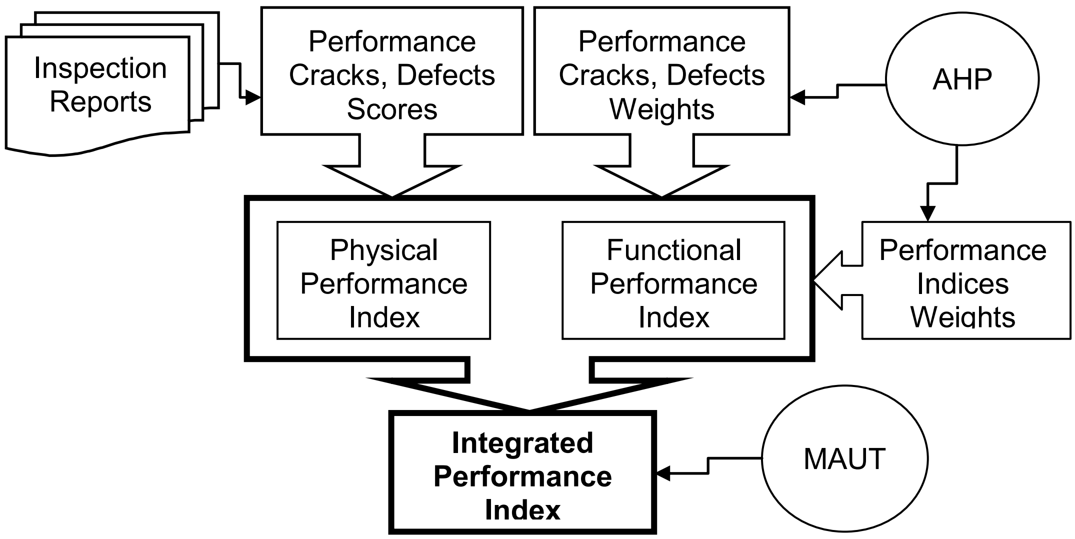


Figure 3.6 Outline of Components Performance Assessment

3.4.1 SUPER Model Performance Factors

Based on the experience, literature review and *Canadian Standards Association* CSA-A23.3 *Concrete Design Handbook*, the SUPER model considers several factors for both the 'Functional Performance' index and the 'Physical Performance' index respectively. The performance factors are illustrated in Figure 3.7.

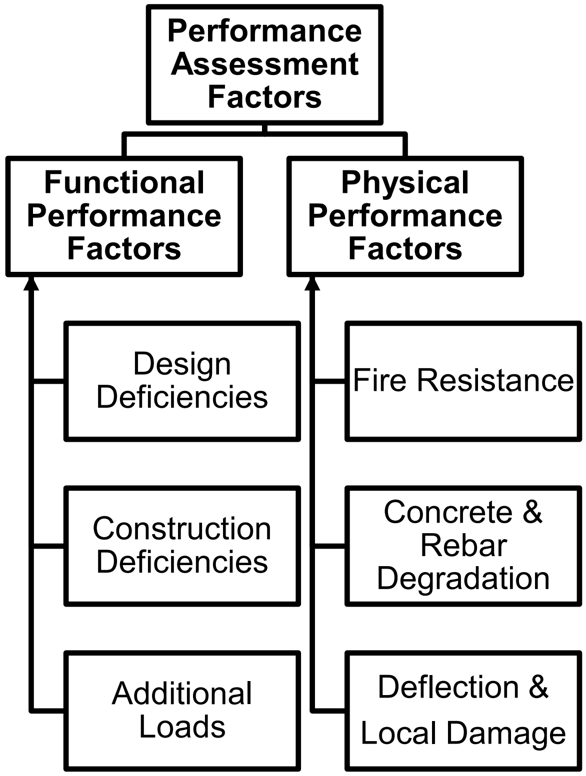


Figure 3.7 SUPER Model Performance Factors

The functional performance factors are defined as follows:

i. ***Construction Deficiencies***: Although structural design can be adequate, construction errors can greatly reduce the functional performance of the component. Construction deficiencies include poor construction methods, non-compliance of the detailing work with the design drawings and specifications, alteration of member sizes during the construction from drawings and specifications, inferior quality of materials and improper concrete mix design, modifications in the structural system by adding and/or removing components without engineering input, and reduction in the amount of steel reinforcement as compared to the design drawings and specifications.

ii. ***Design Deficiencies***: Special care must be taken to avoid gross errors in the design process. This factor indicates the degree of under-capacity if errors exist. Design deficiencies include inadequate beams and columns detailing, lack of ductile design, inadequate anchorage of beam reinforcement, inadequate beam/column joint detailing.

iii. ***Additional loads***: The component originally may be designed for specific loads defined by the codes and regulations according to its usage. However unpredicted additional loads may be applied to the component during its service life. An example to this case could be the new construction of a close building foundation near the retaining wall of a subway station.

The physical performance factors are defined as follows:

i. ***Fire resistance***: Fire resistance generally refers to the property of a component to withstand fire or give protection from it. It is characterized by the ability to confine a fire or to continue to perform during a fire or both. Fire resistance is influenced by the concrete type, the member dimensions, the rebar types, the concrete cover and the restraint and continuity of the member.

ii. ***Concrete and rebar degradation***: physical performance is affected mainly by both concrete and reinforcement degradation processes.

iii. ***Deflection and local damage***: Structural components must perform in a satisfactory manner in service. They should not deflect excessively or vibrate excessively and those local damage cracks which occur should not impair the function or the aesthetics of the structure.

The above-mentioned functional and physical performance factors cannot be quantified. However, they cause deficiencies in the components, primarily cracks and defects. The reader is referred to the literature review for different types of cracks and defects in concrete structures. These cracks and defects can be measured and quantified using scores. Visual cracks and defects are evaluated using the score shown in Table 3.1.

Table 3.1 SUPER Model Visual Inspection Score

Score	State	Description
5	Very Good	✓ New element. ✓ no loss of function
4	Good	✓ Small defects. ✓ Small loss of function.
3	Average	✓ Average defects. ✓ Function is present but minor reparations are required.
2	Poor	✓ Major defects. ✓ Major loss of function.
1	Critical	✓ Severe defects. ✓ Does not comply with codes and regulations. ✓ Under capacity of element.
0	Could not be inspected	N/A.

Table 3.1 is based on the visual inspection scale of the Ministry of Transport of Quebec (MTQ), and reflects the scale used by STM (refer to chapter 2). The SUPER model is based on the visual inspection method, however other methods can be used that reflect the same scale used in Table 3.1.

3.4.2 The Functional Performance Index (P_F)

Referring to expert opinions and the literature, i.e. mainly the *Société de Transport de Montréal* (STM) inspection reports and "*evaluation of structural deterioration guide*", nine structural cracks constitute the Functional Performance index (P_F). The cracks can be divided into two categories: (i) design-based cracks and (ii) construction-based cracks. Design-based cracks are those cracks that are caused by both design deficiencies and additional load factors. The construction-based cracks are those cracks that are caused by construction deficiencies and additional loads as well. The different structural cracks under both categories are illustrated in Figure 3.8.

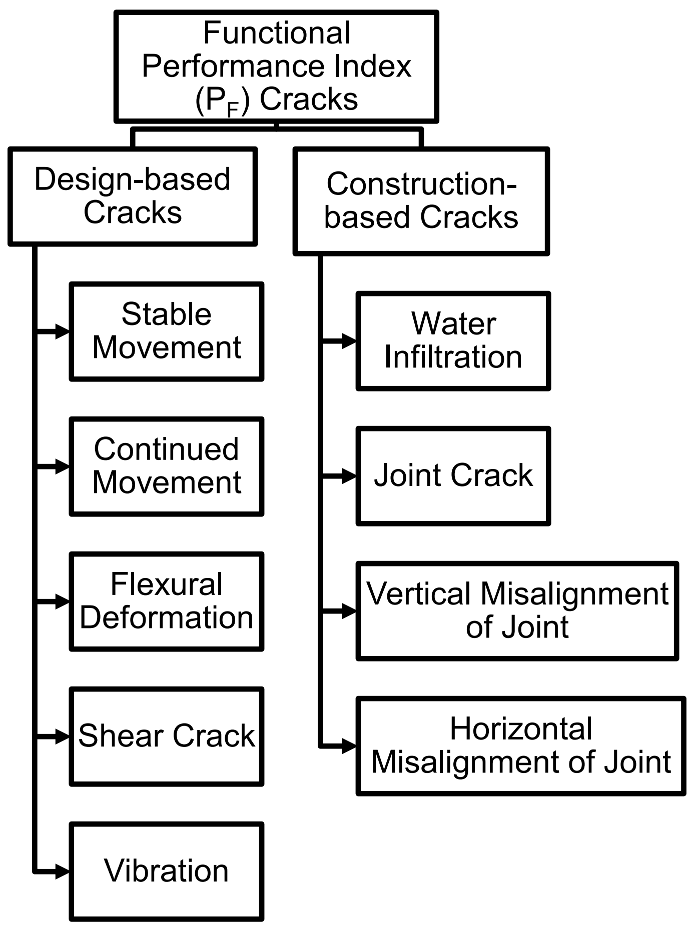


Figure 3.8 Functional Performance Index Cracks

The cracks shown in Figure 3.8 are identified as follows:

i) Design-based cracks category:

1. Stable movement of the component (SM): SM cracks occur when the component moves in a stable manner.
2. Continued increasing movement of the component (CM): CM cracks occur when the component moves in a increased manner.
3. Flexural deformation of the component (FD): FD cracks occur when the component fails to resist flexural stresses.
4. Shear cracks in the component (SHC): SHC cracks occur when the component fails to resist shear stresses.
5. Considerable vibration of the component (V): V cracks occur after considerable vibration of the component.

ii) Construction-based cracks category:

1. Water infiltration in the component (W): W cracks are caused by infiltration of water in the component.
2. Joint crack (JC): JC cracks occur when the joint is not properly designed or constructed.
3. Vertical misalignment of joint (VMJ): VMJ occurs when a beam/column joint is not aligned vertically.
4. Horizontal misalignment of joint (HMJ): HMJ occurs when a beam/column joint is not aligned horizontally.

3.4.3 The Physical Performance Index (P_P)

Referring to expert opinions and the literature, i.e. mainly the *Société de Transport de Montréal* (STM) inspection reports and "*evaluation of structural deterioration guide*", sixteen structural defects constitute the Physical Performance index (P_F). The defects can be divided into two categories: (i) chemical-based and (ii) mechanical-based defects. Chemical-based defects are those related to concrete and rebar degradation caused by chemical attack. The mechanical-based defects are those that are related to local damage and fire resistance caused by physical or mechanical degradation. The different defects under both categories are illustrated in Figure 3.9.

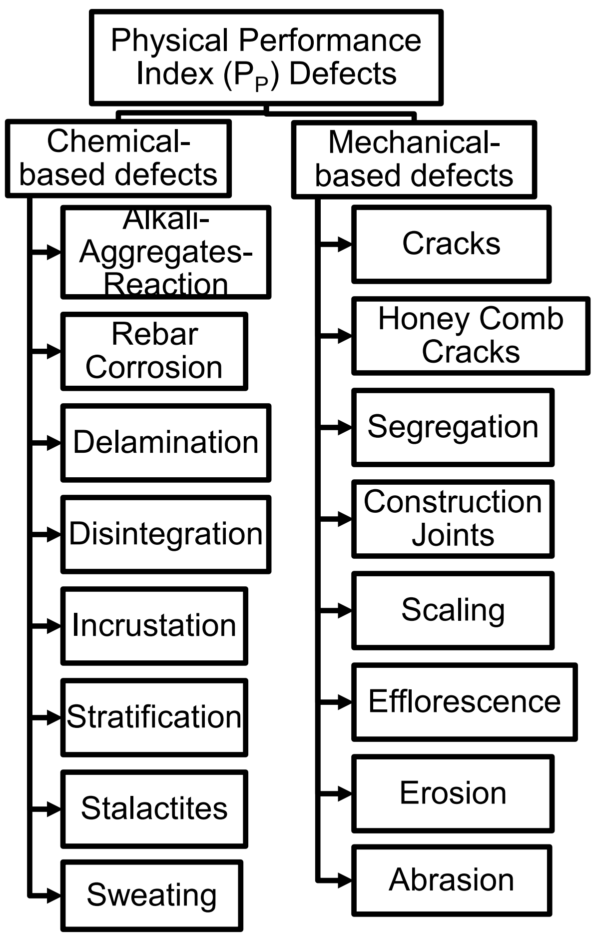


Figure 3.9 Physical Performance Index Defects

The defects shown in Figure 3.9 are identified as follows:

i) <u>Chemical-based defects category</u>:

1. Rebar corrosion (RCOR): RCOR in concrete is an electrochemical process in which metallic iron is converted to the voluminous corrosion product ferric oxide.
2. Delamination (DEL): DEL can be described as a fracture plane, which generally occurs at the interface of a two-course slab or at the level of the rebar due to their corrosion. It is also a separation along a plane nearly parallel to the surface of the concrete.
3. Sweating (SWE): SWE is water seeping through concrete that dissolves water-soluble components (such as calcium hydroxide) in the concrete, which appear on the underside of the surface.
4. Disintegration (DIS): DIS is the disintegration into small fragments or particles due to any cause.
5. Stalactites (STAL): STAL is a viscous gel-like material discharged through a crack in the concrete by the leaching water. For example, calcium carbonate formed by the reaction between the atmospheric carbon dioxide and the calcium hydroxide in concrete under damp conditions.
6. Incrustation (INC): INC is a crust or coating, generally hard, formed on the surface of concrete over a period of time by precipitation of minerals out of leaching water.
7. Alkali-aggregate reaction (AAR): AAR occurs under damp conditions, following the reaction of some form of silica and carbonates in certain

aggregates with the alkali in cement. This reaction produces a gel which occupies more volume and hence, causes expansion and cracks, usually ‘moving away’ from the source of expansion.

8. Stratification (STRAT): STRAT is the separation of over-wet or over-vibrated concrete into horizontal layers with increasingly lighter material toward the top; water, laitance, mortar, and coarse aggregate tend to occupy successively lower positions in that order.

ii) Mechanical-based cracks category:

1. Secondary cracks (C): mainly due to shrinkage, C is due to a rapid drop in temperature of the concrete, such as when concrete slabs and walls are placed on a hot day followed by a cool night. Another cause can be due to insufficient curing of concrete.
2. Efflorescence (EFFL): EFFL is a deposit of salts, usually white, formed on a surface, the substance having emerged from below the surface.
3. Segregation (SEGR): SEGR occurs when the coarse and fine aggregate and cement paste become separated. It happens when concrete is not properly mixed in the forms, due to bad vibration and bad pouring practice.
4. Scaling (SCA): SCA is the local flaking or peeling of the surface mortar of concrete. Most often caused by freeze-thaw damage and/or by a weak cement paste layer at the surface.
5. Erosion (ER): ER is the wearing of the concrete surface by the abrasive action of fluids containing suspended solids.

6. Construction Joint (CJ): named also cold joint, CJ is a discontinuity formed when a concrete surface hardens before the next batch is placed against it.
7. Honey comb cracks (HCC): HCC is a surface condition of irregular voids that result when the mortar does not effectively fill the spaces between the aggregates during vibration. Honeycombing occurs because the concrete mix is under-sanded and/or placing conditions and techniques are poor.
8. Abrasion (ABR): ABR can be defined as the process causing the surface to be worn away by repeated rubbing, rolling, sliding or friction.

3.4.4 The Performance Indices Evaluation

The scores of both the structural cracks and defects based on the defined scale in Table 3.1 are normalized into a performance index from 0 to 1.0 (i.e. 0% to 100% performance) because the score from 0 to 1.0 is meaningful for the integrated performance calculation and evaluation in which the calculation becomes easier. Thus, dividing each crack and defect inspection score (0, 1 to 5) by the maximum score, a normalized score is evaluated using Equations 3.1 and 3.2:

$$\overline{S_C} = ICS / ICS_{MAX} \tag{3.1}$$

$$\overline{S_D} = IDS / IDS_{MAX} \tag{3.2}$$

Where $\overline{S_C}$ *= Normalized Cracks Scores [0 to 1]; ICS = Inspection Cracks Scores defined in Table 3.1 [1 to 5]; and* $ICS_{MAX} = 5$

And, $\overline{S_D}$ *= Normalized Defect Scores [0 to 1], IDS = Inspection Defects Scores, defined in Table 3.1 [1 to 5], and* $IDS_{MAX} = 5$.

Thus, a score of 5 becomes 1 (100% performance); a score of 4 becomes 0.8 (80% performance); a score of 3 becomes 0.6 (60% performance); a score of 2 becomes 0.4 (40% performance); and a score of 1 becomes 0.2 (20% performance or the minimum critical performance).

All structural cracks and defects that affect the functionality of the component on one hand and the physical condition on the other do not have equal weights. In reference to the structural design and analysis code CNBC 2005, some cracks and defects may be more important than others. Since, these structural cracks and defects are evaluated by an inspector independently; the Analytic Hierarchy Process (AHP) can be applied in order to evaluate the importance weights of these cracks and defects relative to each other. The use of AHP is justified since each crack and defect is independent from the rest. It is important to stress that AHP is not the only method that can be used in order to evaluate the cracks and defects weights, other methods can be used adequately. However the present research has chosen the AHP method since it is the easiest method, and the subjectivity of this method can be measured and controlled (contrary to other methods) by checking the consistency of the matrices. The outcome of the AHP analysis is a weight for each crack and defect within each category: 'w_{DbC}' for the design-based cracks, and 'w_{CbC}' for the construction-based cracks; and respectively, the 'w_{CHbD}' for the chemical-based defects, and 'w_{MbD}' for the mechanical-based defects.

The sum of the design-based cracks' weights must be equal to unity according to Equation 3.3:

$$\sum_{\mathrm{DbC}=1}^{5} w_{DbC} = 1.0 \tag{3.3}$$

Where DbC = Design-based Cracks; W_{DbC} = Design-based Cracks' weights.

In addition, the sum of the construction-based cracks' weights must be equal to unity according to Equation 3.4:

$$\sum_{\mathrm{CbC}=1}^{4} w_{CbC} = 1.0 \tag{3.4}$$

Where CbC = Construction-based Cracks; and W_{CbC} = Construction-based Cracks' weights.

The sum of the chemical-based defects' weights must be equal to unity according to Equation 3.5:

$$\sum_{\mathrm{CHbD}=1}^{8} w_{\mathrm{CHbD}} = 1.0 \tag{3.5}$$

Where CHbD = Chemical-based defects; W_{CHbD} = Chemical-based defects' weights.

Finally, the sum of mechanical-based defects weights must be equal to unity according to Equation 3.6:

$$\sum_{\mathrm{MbD}=1}^{8} w_{MbD} = 1.0 \tag{3.6}$$

Where MbD = Mechanical-based Defects; and W_{MbD} = Mechanical-based defects' weights.

The AHP is also used to compare the relative importance of the cracks and defects categories. Thus, the design-based, the construction-based, the chemical-based and the mechanical-based importance weights are evaluated: w_{Db}, w_{Cb}, w_{CHb} and w_{Mb} respectively.

Both the Functional Performance Index (P_F) and the Physical Performance Index (P_P) can be evaluated using the cracks and defects normalized scores (i.e. utilities) and the cracks and defects weights. The Multi-Attribute Utility Theory (MAUT) is applied in order to evaluate the P_F and P_P. The scores (i.e. utilities) have the same scale (0 to 1.0) since they are normalized and the weights vary between 0 and 1.0. The multiplicative form of MAUT is used. This particular form is important and suits the P_F and P_P evaluation since compromises of the cracks and defects do not hold, (i.e. if one of the most weighted cracks and defects is low, the P_F and P_P indices become low).

The Functional Performance Index (P_F) is defined in Equation 3.7:

$$P_F = \left(\prod_{DbC=1}^{5} \overline{S_{DbC}}^{\,w_{DbC}} \right)^{w_{Db}} \times \left(\prod_{CbC=1}^{4} \overline{S_{CbC}}^{\,w_{CbC}} \right)^{w_{Cb}} \tag{3.7}$$

Where $\overline{S_{DbC}}$ = Design-based cracks normalized score, w_{DbC} = Design-based cracks weights; w_{Db} = Design-based category weight;

And $\overline{S_{CbC}}$ = Construction-based cracks normalized score, w_{CbC} = Construction-based cracks weights; w_{Cb} = Construction-based category weight.

Similarly, the Physical Performance Index (P_P) is defined in Equation 3.8:

$$P_P = \left(\prod_{CHbD=1}^{8} \overline{S_{CHbD}}^{\,w_{CHbD}} \right)^{w_{CHb}} \times \left(\prod_{MbD=1}^{8} \overline{S_{MbD}}^{\,w_{MbD}} \right)^{w_{Mb}} \tag{3.8}$$

Where $\overline{S_{CHbD}}$ *= Chemical-based defects normalized score,* w_{CHbD} *= chemical-based defects weights;* w_{CHb} *= chemical-based category weight;*

And $\overline{S_{MbD}}$ *= Mechanical-based defects normalized score,* w_{MbD} *= Mechanical-based defects weights;* w_{Mb} *= Mechanical-based category weight.*

3.4.5 The Integrated Performance Index (P_I) Evaluation

The physical structural performance index is related to general physical fitness or condition of the component, independent of its mission, as it deteriorates due to routine aging, excessive or abusive use or poor maintenance. The functional structural performance index relates to the suitability of the component to its function as intended for the mission. The functional performance index is distinct from, and determined independently from, the physical performance index. Most transit authorities and structural inspectors use the physical condition and functional indicators independently. The integration of these two indices into a one single performance index representing both physical condition and functionality is a complex task.

The two indices (P_P and P_F) do not have the same relative importance. In other words, the P_F could be more or less important than the P_P. Since both indices are evaluated independently, AHP can be used in order to evaluate the importance weights of these two indices: 'w_{PF}' for the functional performance index weight and 'w_{PP}' for the physical performance index weight.

The two indices P_F and P_P can be considered as attributes to the performance. They can also be considered similar to probabilities (since they have values between 0 and 1). In order to evaluate an integrated performance index that considers both indices, two approaches may be used:

i) The first approach considers both indices as attributes, and hence, Multi-Attribute Utility Theory can be applied. In order to consider extreme cases, where the importance of one index to the other is considered, a multiplicative function is used. Thus, the integrated performance index would equal to the weighted P_F multiplied by the weighted P_P.

ii) The second approach considers both indices similar to probabilities. Thus, in order to evaluate the integrated performance index, P_F and P_P are considered (both weighted). In other terms, $P_F \cap P_P$ is evaluated according to the law of probability for independent events.

Both approaches lead to the same equation of the Integrated Performance Index (P_I), defined in Equation 3.9:

$$P_I = P_F^{\,w_{PF}} * P_P^{\,w_{PP}} \tag{3.9}$$

Equation 3.9 is very important because it takes into consideration extreme cases of P_F and P_P. If the P_F is low (very severe functional performance), the P_I is very low no matter the value of P_P and vice versa. The integrated performance index threshold is defined as the limit below which the integrated performance of the component is not allowed. Hence, asset managers do not let the component deteriorate below the threshold level of performance. This leads to the main observation, that if a components' performance is exactly equal to this limit, or threshold, it is entitled to major maintenance and repair. This last observation is clarified and justified if the manager analyzes carefully the scores shown in Table 3.1, which in turn is extremely important. Table 3.1 indicates that if a component has a visual score of '2', then this component has a 'POOR' performance level and hence is characterized by both 'Major Defects' and 'Major Loss of function'.

It can be concluded that for a score of '2', both the condition and functional performances are at a limit level. A question here can be raised: does the asset manager allow the component to have a performance level below the score of '2' or 'POOR'? In other words, does the asset manager allow the structural component to have a 'Critical' performance level? The answer is straight forward: no infrastructure asset manager allows the component structural performance to be 'Critical' since it becomes dangerous to the public especially if the infrastructure (subway network) is a major public facility.

In conclusion, public infrastructure cannot have a 'Critical' level of performance, especially the subway network. Thus, a score of '2', which in turn equals a performance level of 2/5 = 0.4, or 40% can be considered a limit or threshold. Another limit is the minimum performance where it is considered to be at a 'Critical' level, or score of '1', which equals a performance level of 1/5 = 0.2, or 20%. Thus, the SUPER model considers that the integrated performance index threshold is equal to 0.4, and the minimum integrated performance index level is equal to 0.2. The above-mentioned limits are double checked with experts.

3.5 COMPONENTS PERFORMANCE MODELING

The Integrated Performance Index (P_I) is evaluated for each inspection performed. It is evaluated for all the components of each station, tunnel and auxiliary structure independently. The SUPER model evaluates the performance curve of the components based on their performance assessment. The procedure for the performance modeling of the components is outlined in Figure 3.10.

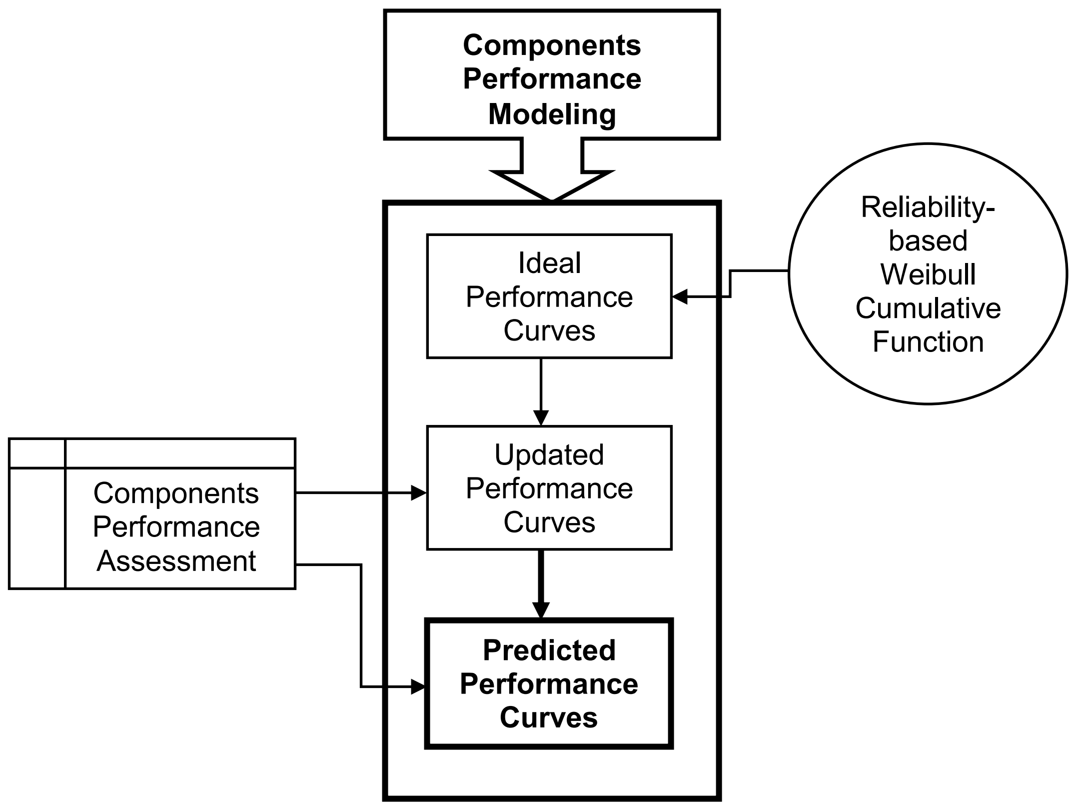


Figure 3.10 Components Performance Modeling Outline

The modeling starts by evaluating an ideal performance curve. Using the integrated performance index calculated from each inspection, the performance curve for each component is updated. After the final update, the predicted performance curve is produced.

3.5.1 Ideal Performance Curve

The present research is concerned with modeling the change in the structural integrated performance of the components over time. After evaluating the structural Integrated Performance Index (P_I) for each component, and in reference to the literature review, the most adequate form to present the performance (P_I) over time, is the inverse cumulative Weibull probability distribution function.

As discussed in Chapter 2, other models can be used, but these models have not proven to be effective for subway systems. The Weibull reliability function has many advantages in which it is the most appropriate technique for modeling the performance of the structural components within subway networks. The Weibull reliability function has proven to be one of the best functions to represent concrete deterioration. Depending on its parameters, the function starts at the maximum performance level and remains constant for a certain time (slope equals zero). This is true, since concrete structures remain functional and typically have an excellent condition for a certain time after construction. However, after this ‘stable’ time (steady state), concrete structural performance starts decreasing, (i.e. deterioration occurs); the Weibull reliability function similarly starts decreasing (negative slope). The concrete deterioration speed decreases near the end of its service life. Similarly the slope of the Weibull reliability function decreases and the function passes through an inflection point.

The second advantage enforces the justification of the usage of the Weibull reliability function. Subway network inspection reports are few and the deterioration model must consider this fact. The Weibull reliability function, while modeling the deterioration, uses a few number of inspections. The Weibull reliability function does not need a lot of historical inspection data. Third, the Weibull reliability function can be easily used to model the components up to network performance, in contrast to other methods. Finally, the Weibull reliability function parameters are easily calculated and are also significant figures.

The main drawback of the Weibull function is the evaluation of its parameters. The SUPER model overcomes this difficulty by adding important conditions that helps determining the parameters easily and without difficulty. It is difficult to obtain a Weibull reliability shape performance function that considers the history of inspection for components and their maintenance history, if applicable. The SUPER model overcomes this difficulty by first modeling an Ideal Performance Curve. It subsequently updates the performance curve for each inspection. At the end, the updated performance curve or the predicted performance curve is constructed after considering the last inspection. With reference to the literature review (Weibull analysis), the Weibull probability distribution function is defined in Equation 3.10:

$$f(t) = \frac{\delta}{\tau}\left(\frac{t-\alpha}{\tau}\right)^{\delta-1} \times e^{-(\frac{t-\alpha}{\tau})^{\delta}} \qquad \text{For } t > \alpha \qquad (3.10)$$

Where α *= location parameter,* τ *= scale parameter,* δ *= shape/slope parameter, and t = time.*

The cumulative Weibull distribution function (cdf) is defined in Equation 3.11:

$$F(t) = 1 - e^{-(\frac{t-\alpha}{\tau})^{\delta}} \tag{3.11}$$

Hence, the Weibull reliability function of a distribution is simply one minus the cumulative distribution function (cdf). The reliability function for the Weibull distribution is given by Equation 3.12 and illustrated in Figure 3.11:

$$R(t) = 1 - F(t) = e^{-(\frac{t-\alpha}{\tau})^{\delta}} \tag{3.12}$$

The Ideal Performance Curve (IPC) has the same shape of Equation 3.12, and is defined in Equation 3.13:

$$PI^{IPC}(t) = \alpha \cdot e^{-(\frac{t}{\tau})^{\delta}} \tag{3.13}$$

Where IPC = Ideal Performance Curve, t = time, e = exponential, α *= Initial condition factor or location parameter,* τ *= Service Life (SL) adjustment parameter, or scale parameter,* δ *= Deterioration parameter, or shape/slope parameter.*

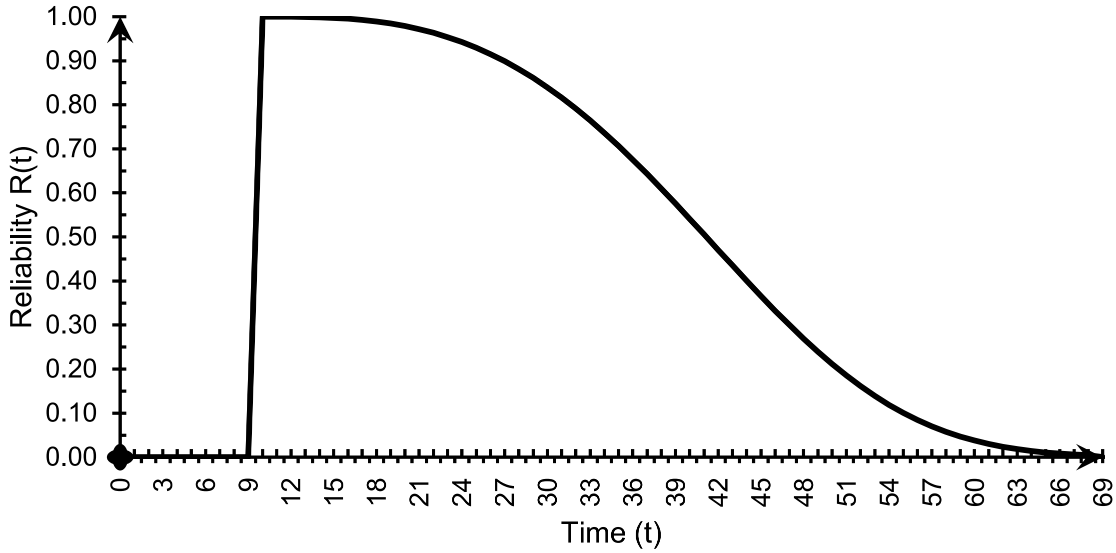


Figure 3.11 Weibull Reliability Curve

The IPC has the following characteristics:

1) At initial time (t = 0), the slope of the curve equals zero as shown is Equation 3.14:

$$\frac{\partial(P_I^{\ IPC})}{\partial t} = P_I^{\ IPC'}(t) = 0 \tag{3.14}$$

2) The ideal Service Life (SL) is assumed to be 100 years for infrastructure concrete elements.

3) The Useful Service Life (USL) is the life of the structure at the minimum acceptable performance, or the performance threshold.

4) The performance threshold equals 2/5=0.4

5) The minimum performance is equal to 1/5 = 0.2

6) The failure rate is defined as $\frac{1}{\tau}$, or the inverse of the service life adjustment parameter.

The IPC must be constructed such that as concrete wear sets in, the curve goes through an inflection point and then decreases sharply. Thus, the performance curve decreases as time increases (i.e. the deterioration parameter δ should be more than 1 ($\delta > 1$) and an integer). In order to construct the Ideal Performance Curve, the following conditions must be met:

i. At time t= 0, the P_I^{IPC} = 1.0 (maximum performance), thus:

$$1.0 = \alpha \cdot e^{-\left(0/\tau\right)^{\delta}} = \alpha$$

So α = 1.0

ii. At time t = 0, the slope or the tangent is zero, so:

$$\frac{\partial(P_I^{IPC})}{\partial t} = P_I^{IPC'}(t) = 0$$

iii. At time t = SL = 100 years, P_I^{IPC} = 0.2 (minimum performance), so if:

$$0.2 = 1 \cdot e^{-\left(100/\tau\right)^{\delta}}$$ then,

$\ln(0.2) = \ln(1) - (100 / \tau)^{\delta}$ and,

$\ln(1) - \ln(0.2) = 0 - \ln(0.2) = -\ln(0.2) = (100 / \tau)^{\delta}$ hence,

τ is defined in Equation 3.15:

$$\tau = \frac{100}{\left[-\ln(0.2)\right]^{1/\delta}} = \frac{100}{\sqrt[\delta]{\left[-\ln(0.2)\right]}} \tag{3.15}$$

iv. $\delta > 1$ and should be an integer. So $\delta = 3$ (1, 2, 4 etc…will not bring the shape of the curve to the desired one).

In addition to the above, at time t = USL, the P_I^{IPC} = 0.4 (threshold performance). Substituting in Equation 3.13, the P_I of the IPC is defined in Equation 3.16:

$$P_I(t)^{IPC} = 1 \cdot e^{\left[\frac{\ln(0.2)t^3}{100^3}\right]} \tag{3.16}$$

Calculating τ: τ = 85.33 years

Thus, the P_I of the IPC is defined in Equation 3.17:

$$P_I(t)^{IPC} = 1 \cdot e^{-\left(t/85.33\right)^3} \tag{3.17}$$

Where P_I = integrated performance index at time t, t = time, IPC = Ideal Performance Curve.

Figure 3.12 illustrates the shape of the Ideal Performance Curve.

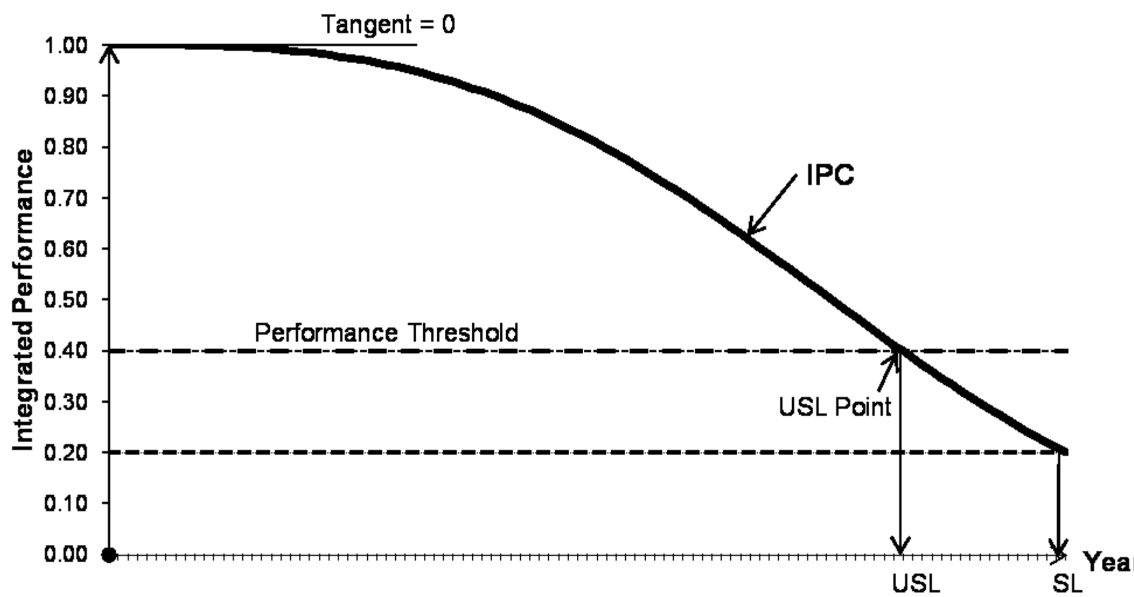


Figure 3.12 Ideal Performance Curve (IPC)

3.5.2 Updated Performance Curve

After constructing the Ideal Performance Curve, the SUPER model updates the performance curve after performing every inspection. The IPC represents a theoretical 'desired' performance curve for the component. However, the real reduction of performance over time is best represented in the Updated Performance Curve (UPC). For each inspection, the P_I is evaluated for all inspected components. The updated curve must pass through this specific P_I point. From this inspection (or point), new Weibull parameters are calculated. The major advantage of the Weibull reliability function update is the ease in calculating the Weibull parameters. After each inspection, the UPC is constructed and the Updated Service Life ($USL_{Updated}$) is calculated. The UPC best represents the real performance of the component considering the inspection done. It should be noted that the updated curve is not necessarily below the ideal one. In order to construct the UPC, the following conditions should be met:

i. At the construction year, at time t= 0, the P_I = 1.0 (maximum), thus:

$$1.0 = \alpha \cdot e^{-\left(0/\tau\right)^{\delta}} = \alpha \quad \text{so} \qquad \alpha = 1.0$$

ii. At time t = 0, the slope or the tangent is zero, so:

$$\frac{\partial (P_I^{UPC})}{\partial t} = P_I^{UPC'}(t) = 0$$

iii. At the time of inspection or t_i , the integrated performance index P_{Ii} is between 1.0 and 0.2, so if:

$P_{Ii} = 1 \cdot e^{-\left(t_i/\tau\right)^{\delta}}$, thus

$\ln(P_{Ii}) = \ln(1) - (t_i / \tau)^{\delta}$, so

$\ln(1) - \ln(P_{Ii}) = 0 - \ln(P_{Ii}) = -\ln(P_{Ii}) = (t_i / \tau)^{\delta}$

Hence, τ is defined in Equation 3.18 as follows:

$$\tau = \frac{t_i}{\left[-\ln(P_{Ii})\right]^{1/\delta}} = \frac{t_i}{\sqrt[\delta]{\left[-\ln(P_{Ii})\right]}} \tag{3.18}$$

Where, t_i = inspection time, and P_{Ii} = integrated performance index at time t_i.

iv. $\delta > 1$ and should be an integer. So, $\delta = 3$ (1, 2, 4 etc…will not bring the shape of the curve to the desired one).

Substituting τ (evaluated in Equation 3.18) in Equation 3.12, the P_I of the UPC is defined in Equation 3.19:

$$P_I(t)^{UPC} = 1 \cdot e^{\left[\frac{\ln(P_{Ii}) \times t^3}{t_i^3}\right]} \tag{3.19}$$

Shuffling the previous equation, the P_I of the UPC is defined in Equation 3.20:

$$P_I(t)^{UPC} = 1 \cdot e^{\ln(P_{Ii})\left(t/t_i\right)^3} \tag{3.20}$$

Where, t_i = inspection time, and P_{Ii} = integrated performance index at time t_i.

Figures 3.13 and 3.14 represent the Updated Performance Curves (UPC) after a first and a second inspection respectively.

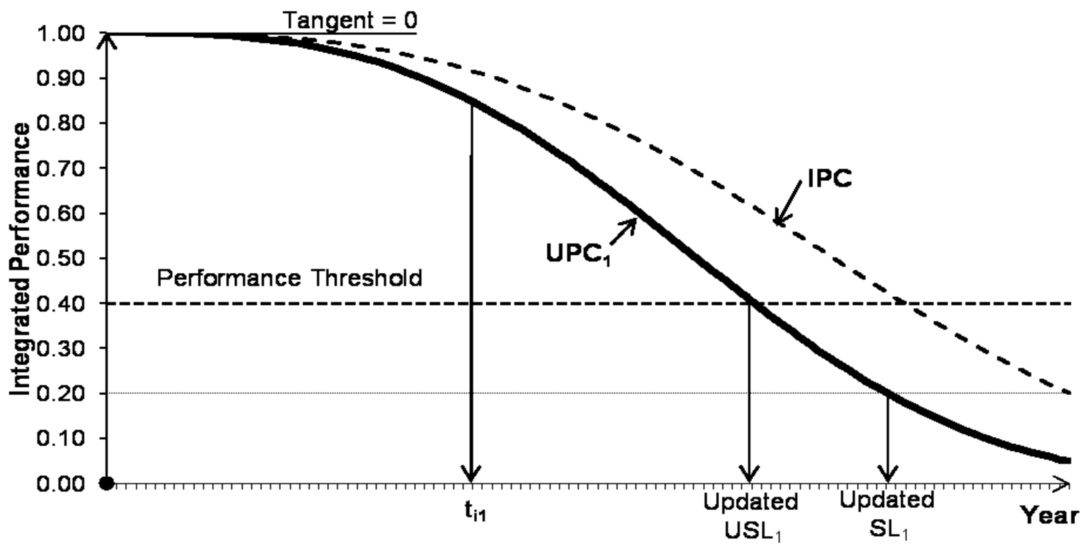


Figure 3.13 Updated Performance Curve after the First Inspection

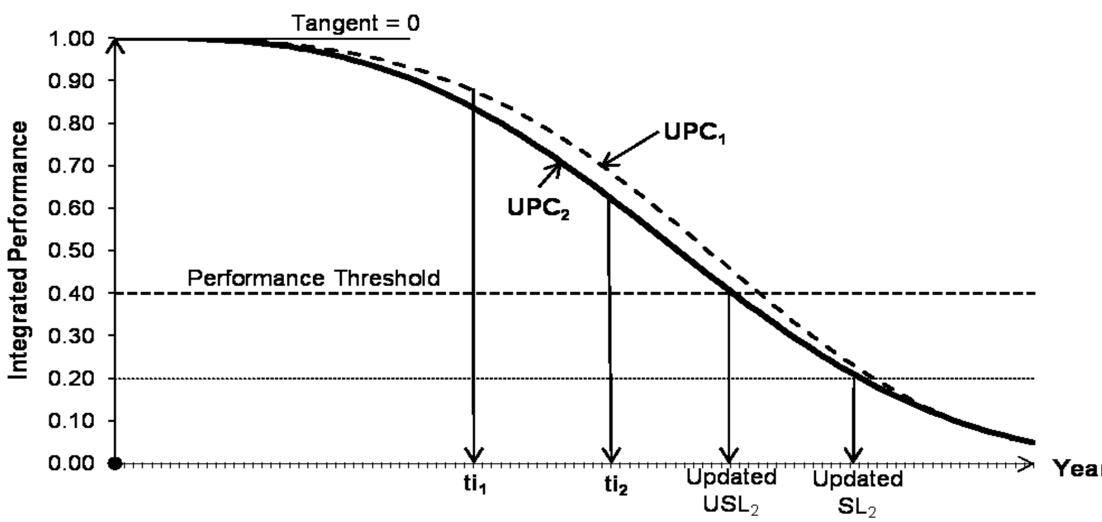


Figure 3.14 Updated Performance Curve after the Second Inspection

3.5.3 Predicted Performance Curve

The final Updated Performance Curve (following the last inspection) is considered the Predicted Performance Curve (PPC). The PPC considers the inspection information about the history of the component till the last one. The

PPC predicts the useful service life (the Predicted Useful Service Life PUSL), and the future integrated performance (the Predicted Integrated Performance P_I^{PPC}). The PPC can have two forms depending on whether a Maintenance and Rehabilitation (M&R) action is done on the component. If no M&R action is done, the PPC follows Equations 3.19 and 3.20; (i.e. same as the latest UPC evaluated). If an M&R action is done at a specific time (t_m), the PPC is divided in two parts: before the M&R and after the M&R. In the case of before the M&R action, the PPC is exactly the same as the UPC. Thus, following the steps of the UPC equation derivation, and substituting the M&R time (t_m) for t_i, and the integrated performance index at directly before the M&R (P_{Im}) for P_{Ii}, the PPC before the M&R is defined in Equation 3.21:

$$P_I(t)^{PPC} = 1 \cdot e^{\ln(P_{Im})\left(t/t_m\right)^3} \qquad (3.21)$$

Where t_m = time of M&R action, and P_{Im} = Performance directly before the M&R action.

After the M&R action (at t_m +1), the shape of PPC does not differ from the UPC function, however at time = t_m + 1, the improved performance is defined by Equation 3.22:

$$P_{IM} = P_{Im} + \Delta M \qquad (3.22)$$

Where P_{IM} = Performance improved directly after the M&R action, and ΔM = M&R action performance improvement.

Substituting in Equation 3.21, the PPC after the M&R action is defined in Equation 3.23:

$$P_I(t)^{PPC} = P_{IM} \cdot e^{\ln(P_{Ii}) \cdot (t-t_m+1)^3 / t_i^3} \tag{3.23}$$

Where t_i = inspection time after the M&R action, P_{Ii} = Performance after the M&R action,

P_{IM} = Performance improved directly after the M&R action, and t_m = time of M&R action.

Figure 3.15 represents the PPC without maintenance, and Figure 3.16 shows the PPC with a specific maintenance done at time (t_m).

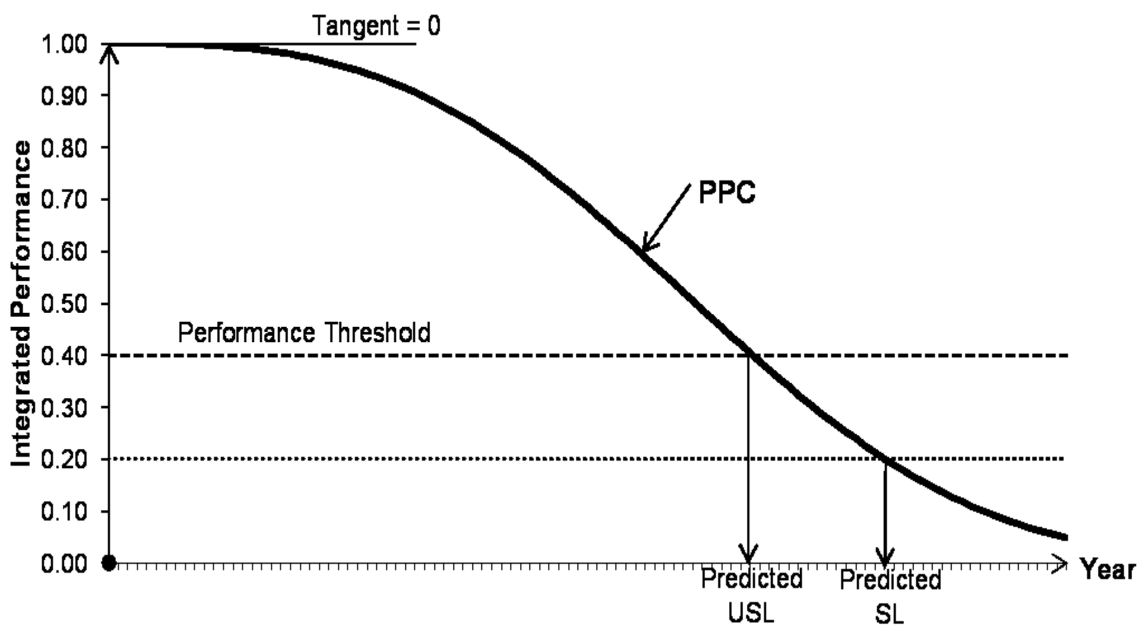


Figure 3.15 PPC with No Maintenance

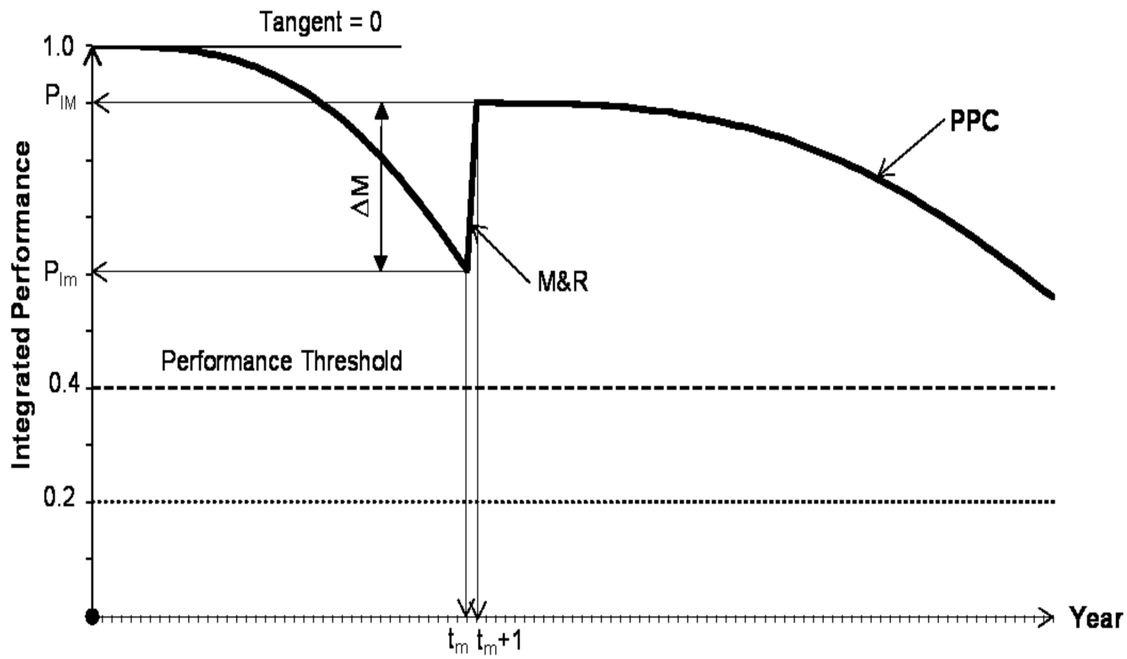


Figure 3.16 PPC with M&R Action

By summing up all the contributions, starting from the components performance assessment at each inspection, a performance model is evaluated. The performance model develops an ideal performance curve and then updates it according to the performance assessment. Due to the high number of components in stations, tunnels and auxiliary structures and the few number of inspection reports, many components do not have an inspection record (or have never been inspected). In this case, the Ideal Performance Curve applies to these components. It should also be stressed that for components, which have more than two inspection records, the predicted performance curve depends on the last inspection. If at the last inspection an M&R action is applied, (i.e., no inspection record after the M&R action), the SUPER model assumes the performance curve after the M&R to be the Ideal Performance Curve. Also, if an

M&R action is applied and the transit authority did not assess the improvement of performance due to this action, the SUPER model assumes that this improvement leads to an integrated performance of 0.9 (90%); assuming that no M&R action improves the performance to a 100% level.

3.6 SYSTEMS PERFORMANCE MODELING

This part of the SUPER model evaluates the integrated Predicted Performance Curves for different systems, which are defined in the network hierarchy to include stations, tunnels and auxiliary structures. The systems performance modeling is outlined in Figure 3.17.

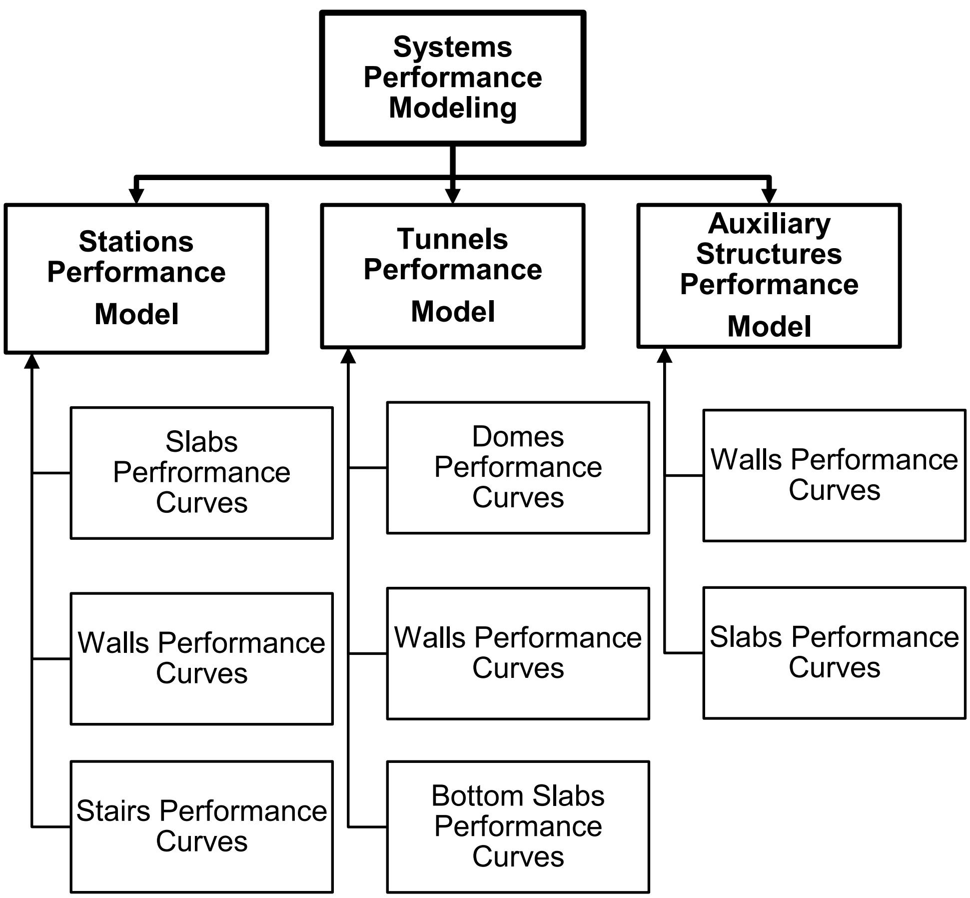


Figure 3.17 Systems Performance Modeling Outline

In a generic subway network, there exist three major types of structures: stations, tunnels and auxiliary structures. The SUPER model considers each type of these structures a system. Hence, the model considers a station system, a tunnel system and an auxiliary structure system.

3.6.1 Station System Performance Model

This section presents the integrated predicted performance evaluation for a station system. Figure 3.17 illustrates a free body diagram of a generic station. The station system consists of the following components: (i) external slab (SE), (ii) internal slab (SI), (iii) external wall (WE), (iv) internal wall (WI), internal stairs (TI), and (v) external stairs (TE). These components are distributed over the floors. A typical station consists of the train platform floor (level 0), the mezzanine floor (level 1), and then the building floors (levels 2 to *n*, where *n* is the total number of floors as illustrated in Figure 3.18. The station is assumed to be symmetrical in the free body diagram of Figure 3.18.

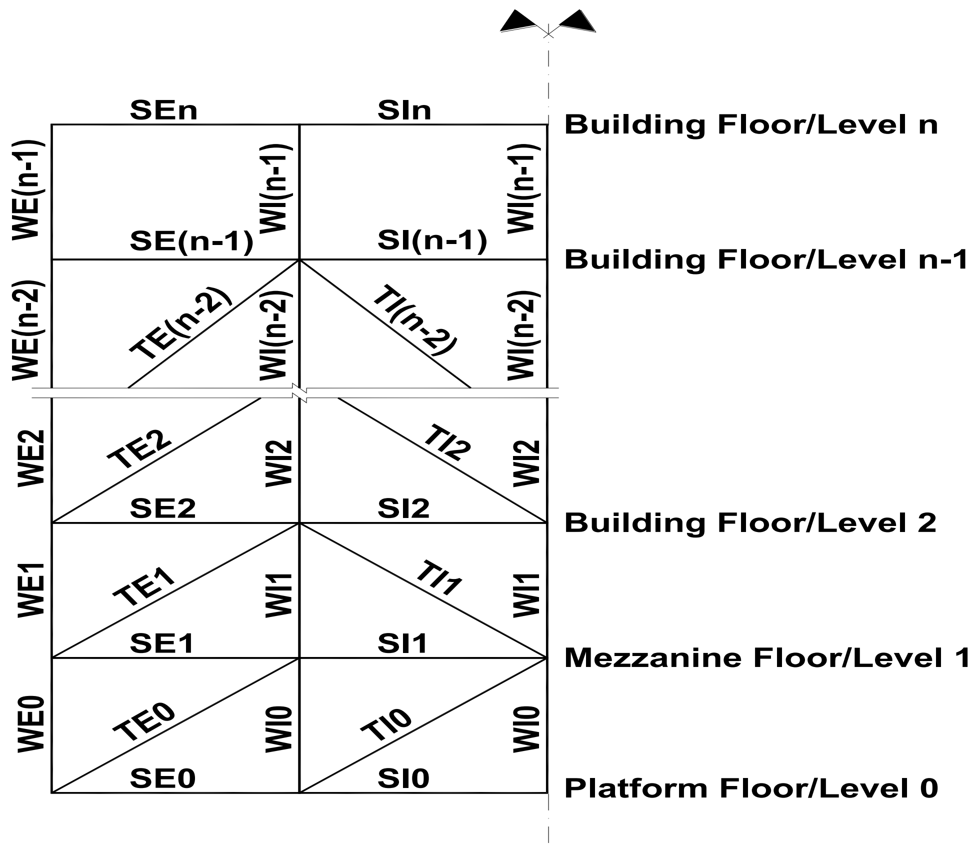


Figure 3.18 Station System Free Body Diagram

In order to evaluate the predicted integrated performance of the station, the SUPER model utilizes the series-parallel system reliability technique. Therefore, the station is composed of components in series, parallel and/or a combination of both. In general, a parallel system is called a redundant system. Thus, if one component of the parallel system fails, there are alternative components that allow the system to function successfully. If there is at least one component functioning, it is sufficient for the parallel system to function. Hence, the parallel system fails only if all the components fail. Furthermore, in a parallel system all components operate simultaneously. Thus, the performance of a parallel system is shown in Figure 3.19 and defined in Equation 3.24.

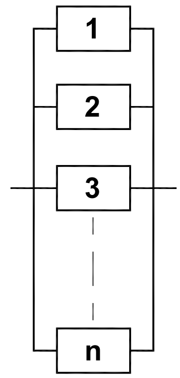


Figure 3.19 Parallel System Model

$$P(x_1, x_2, x_3 \ldots x_n) = 1 - (1-p_{x1})*(1-p_{x2})*(1-p_{x3})\ldots*(1-p_{xn}) \quad (3.24)$$

Where P(x) = System performance, x_1, x_2, x_3,…x_n = n-components, p_{x1}, p_{x2}, p_{x3},…p_{xn} = performance of n-components.

Moreover, as a general definition, all components of a series system must function for the system to function. Hence, if one component fails, the whole series system fails. The order of the components is of no importance. Hence, the performance of a series system is shown in Figure 3.20 and defined in Equation 3.25:

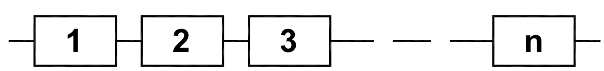


Figure 3.20 Series System Model

$$P(x_1, x_2, x_3 \ldots x_n) = p_{x1} * p_{x2} * p_{x3} \ldots * p_{xn} \quad (3.25)$$

Where P(x) = System performance, x_1, x_2, x_3,…x_n = n-components, p_{x1}, p_{x2}, p_{x3}…p_{xn} = performance of n-components.

The rationale of constructing a parallel-series system for a subway station is related to the structural behavior of station components. It must be stressed that performance means that the structural components still exist and no collapse has occurred. Hence, progressive failure is not considered. This consideration is important and justified since no performance is practically allowed below the performance threshold (P_I = 0.4). Modeling series and parallel system of a structure is a subjective matter, thus each engineer or manager may consider his own ideas and views. The present research models a station depending on the performance and considering user safety. Thus, it is assumed that if a component does not perform and is considered dangerous, the whole station could be closed to the public. Thus, structurally, if a slab (and similarly stairs) fails to perform and its supports walls or beams function, it is a local failure of performance (i.e. below threshold), and there are other ‘routes’ or slabs that function independently of the “failing” (or non-performing) slab. Thus, at each floor, all slabs must “fail” to perform in order to render the slab system as non-performing. Hence at each floor, the slab system is a redundant system and can be considered a parallel system. The stair system is similar to the slab system. However the wall system differs. If any wall “fails” to perform, the whole station becomes non safe, and thus does not perform. A wall failure of performance (performance below threshold) entails with it all adjacent slabs failures. Thus the wall system is considered a system in series. It should be stressed that the components are independent (similar to independent probabilities). Figure 3.21 illustrates the station system series-parallel performance model.

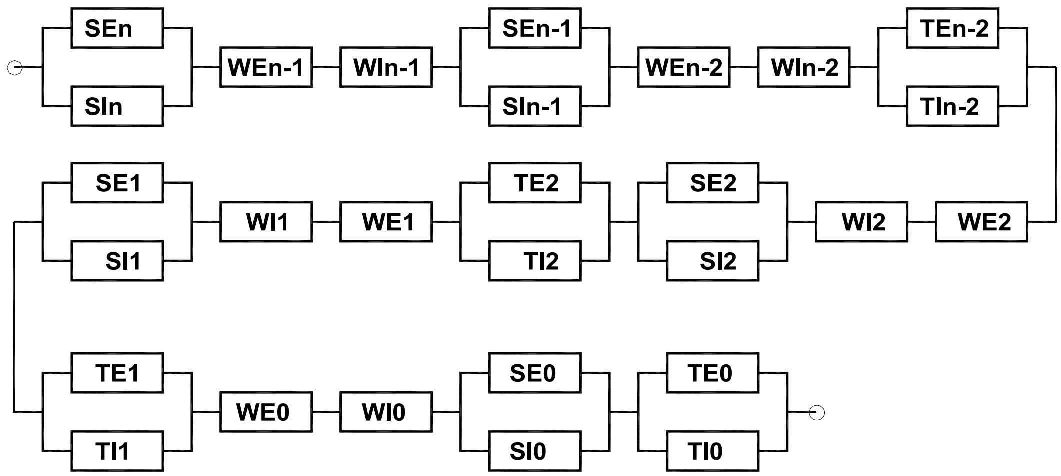


Figure 3.21 Station System Performance Model

Based on this series-parallel performance model, the station performance model is defined in Equation 3.26:

$$P_{STA} = [\prod_{i=0}^{n-1}(P_{WEi}P_{WIi})] * [1 - \prod_{i=0}^{n}(1 - P_{SEi})(1 - P_{SIi})] * [1 - \prod_{i=0}^{n-1}(1 - P_{TEi})(1 - P_{TIi})] \quad (3.26)$$

Where P_{STA} = Station performance, i = 1 to n are the station floors, P_{WE} = Exterior Wall performance, P_{WI} = Interior Wall performance, P_{SE} = Exterior Slab performance, P_{SI} = Interior Wall performance, P_{TE} = Exterior Stair performance, P_{TI} = Interior Stair performance.

The integrated station performance does not strictly follow a cumulative Weibull function. The station performance curve can be constructed by calculating the performance at each year using Equation 3.26.

3.6.2 Tunnel System Performance Model

The integrated predicted performance for a tunnel system is evaluated. Figure 3.22 illustrates a generic tunnel free body diagram. The tunnel system consists of the following components: (i) dome or arch (D), (ii) walls (W), and (ii) bottom slab (BS).

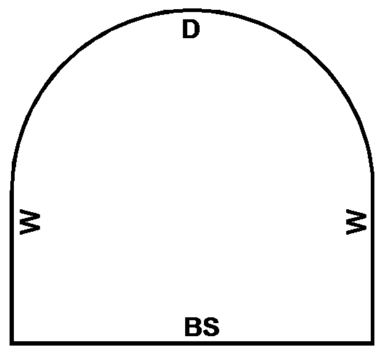


Figure 3.22 Tunnel System Free Body Diagram

In order to evaluate the predicted performance of a tunnel system, the SUPER model utilizes the series-parallel system reliability technique. Hence, the tunnel is composed of components in series, parallel and/or a combination of both. Refer to Figures 3.19 and 3.20 and Equations 3.24 and 3.25 for the definitions of systems in parallel and in series. The rationale of constructing a parallel-series system model for a tunnel depends on the structural behavior of the tunnel components themselves. Structurally, if either the dome, walls or bottom slab “fail” to perform (performance below threshold) the tunnel system fails. Thus the tunnel system is considered a system in series. It should be stressed that the components are independent (similar to independent probabilities). Figure 3.23 illustrates the tunnel system series performance model.

Figure 3.23 Tunnel System Performance Model

Based on the series performance model, the tunnel performance model is defined in Equation 3.27:

$$P_{TUN} = P_D{*}P_W{*}P_{BS} \qquad (3.27)$$

Where P_{TUN} = Tunnel performance, P_D =Dome performance, P_W = Walls performance, P_{BS} = Bottom Slab performance.

Here also, the integrated tunnel performance may or may not follow strictly a cumulative Weibull function. The tunnel performance curve can be constructed by calculating the performance at each year using Equation 3.27.

3.6.3 Auxiliary Structure System Performance Model

The integrated predicted performance for auxiliary structures is evaluated as well. The auxiliary structures are generally service structures constructed for the following usage types: A) dewatering wells, B) rectifier stations, C) ventilation wells, and D) mechanical ventilation wells. The four types have similar components. Thus, the auxiliary structures system consists of the following components: (i) walls (W), (ii) top slab (ST) and (iii) bottom slab (SB). Figure 3.24 illustrates a generic auxiliary structure free body diagram.

In order to evaluate the predicted performance of the auxiliary structures system, the SUPER model utilizes the series-parallel system reliability technique. Therefore, each auxiliary structure is composed of components in series, parallel and/or a combination of both. Refer to Figures 3.19 and 3.20 and Equations 3.24

and 3.25 for the definitions of systems in parallel and in series. The rationale of constructing a parallel-series system for an auxiliary structure depends on the structural behavior of its components themselves. Structurally, if either the walls or both slabs “fail” to perform (performance below the threshold) the structural system fails. It should be stressed that the components are independent. Figure 3.25 illustrates the auxiliary structure system series-parallel performance model.

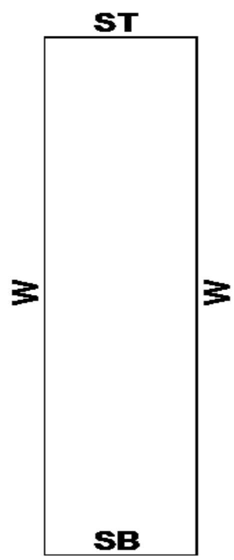


Figure 3.24 Auxiliary Structure System Free Body Diagram

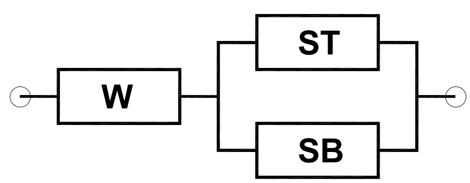


Figure 3.25 Auxiliary Structure System Performance Model

Based on the series-parallel performance model, the auxiliary structure performance is defined in Equation 3.28:

$$P_{AS} = P_{W.} [1-(1-P_{ST})*(1-P_{SB})] \tag{3.28}$$

Where P_{AS} = Auxiliary Structure performance, P_W = Walls performance, P_{ST} = Top Slab performance, P_{SB} = Bottom Slab performance.

The integrated auxiliary structure performance may or may not follow strictly a cumulative Weibull function. The auxiliary structure performance curve can be constructed by calculating the performance at each year using Equation 3.28.

3.7 SUBWAY LINE PERFORMANCE MODELING

A line consists of all the stations, tunnels and auxiliary structures that physically exist on the line. Therefore, the line is comprised of the three types of connected systems. The line performance can be modeled using the series-parallel model. If a particular station does not perform, routing using other modes of transit transportation can be used (buses for example) to go around this particular station. It is only when all stations do not perform that the line stops performing. Hence, the stations in a line can be modeled in parallel. Similarly for a tunnel, if one tunnel section does not perform, the users can be transferred using a bus system to another section. Hence, the tunnel system in a line is a redundant system, and can be modeled in parallel. It should be stressed that the tunnels adjacent to a particular station are independent of the station itself. Therefore, if a particular station stops performing, the adjacent tunnels may still perform adequately. The auxiliary structures model follows the same rationale as well, and is modeled in parallel. Finally, all the stations, with all the tunnels and the auxiliary structures are in series. If all the stations fail to perform, the line stops performing. Similarly, if all the tunnels fail to perform, the line stops performing.

The same can be said for auxiliary structures. It should be stressed that the systems are independent (similar to independent probabilities). The line performance model is shown in Figure 3.26.

Mathematically, the line performance model is defined in Equation 3.29:

$$P_{LINE}(t) = \left[1 - \prod_{j=1}^{m}\left(1 - P_{STAj}(t)\right)\right] * \left[1 - \prod_{j=1}^{m}\left(1 - P_{TUNj}(t)\right)\right] * \left[1 - \prod_{j=1}^{m}\left(1 - P_{ASj}(t)\right)\right] \qquad (3.29)$$

Where P_{LINE} (t) = Line performance, $P_{STA\ j}$ (t) = performance of station j, $P_{TUN\ j}$ (t) = performance of tunnel j, $P_{AS\ j}$ (t) = performance of auxiliary structure j, j = system, j = 1 to m, m = total number of systems in a line.

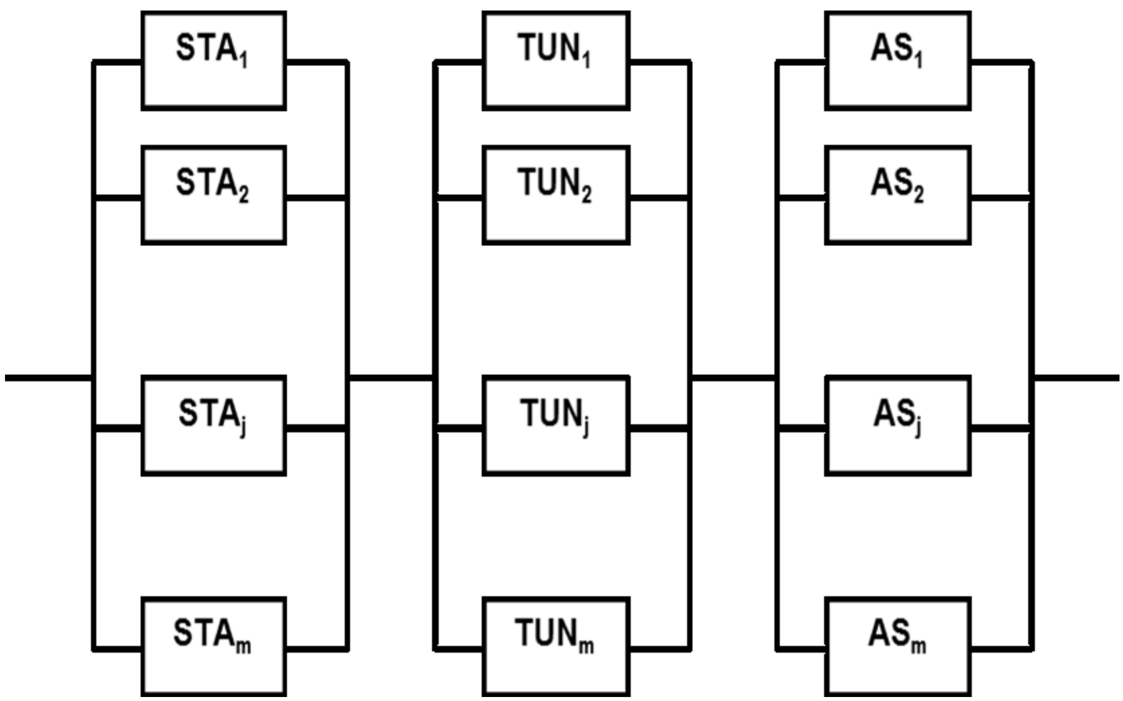


Figure 3.26 Subway Line Performance Model

3.8 SUBWAY NETWORK PERFORMANCE MODELING

The network performance is the overall performance of all lines forming the subway network. If one line fails to perform, the other lines are not affected, thus the lines are redundant. This means that all lines must fail to perform in order for the network to stop performing. Therefore, the lines in a network can be modeled in parallel. It should be stressed that the lines are independent (similar to independent probabilities). The network performance model is illustrated in Figure 3.27.

Mathematically, the network performance model is defined in Equation 3.30:

$$P_{NETWORK}(t) = 1 - \prod_{k=1}^{u}(1 - P_{LINE}(t)_k) \tag{3.30}$$

Where $P_{NETWORK}(t)$ = network performance, $P_{Line}(t)_k$ = performance of line k, k = Line, k = 1 to u, u = total number of lines in a network.

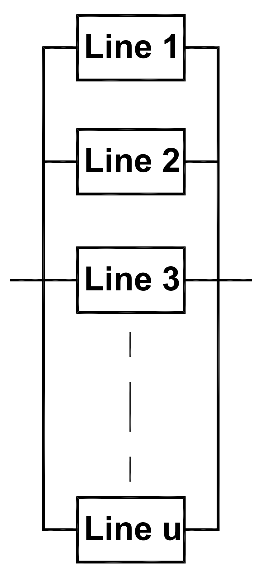


Figure 3.27 Subway Network Performance Model

3.9 THE SUPER MODEL SOFTWARE

The mathematical and graphical elements of the SUPER model, which are developed in the previous sections, are incorporated in a software program, entitled ‘the SUPER Model Software’. Transit managers need not to go through any detail of the mathematical models while using the SUPER model software. The software should be user friendly, be easy to use and conceal the complications and complex calculations of the model. The SUPER model software is an application that uses the C++ programming language. The user is guided through windows that ask for the input and automatically display the outputs. The software inputs consist of the following:

- Network hierarchy,
- Systems information (systems on each line, number of floors for stations, year of construction, year of inspection, and M&R actions),
- Cracks and defects' scores for the systems’ components.

The software outputs consist of the following:

- The performance indices (P_P, P_F, and P_I),
- The integrated performance curves for the systems, lines and network.

The SUPER model software explanation is extended in chapter 6 in detail.

3.10 SUMMARY

The SUPER model, which assesses the structural performance of different subway components, systems, lines and network, has been developed. It identifies the subway network hierarchy where the network is comprised of lines. Each line consists of stations, tunnels and auxiliary structures physically on that line. Each station consists of several components, such as floor slabs, stairs and walls. The tunnel consists of a dome (arch), side walls and a bottom slab, whereas, the auxiliary structure consists of a top and bottom slab and side walls.

Physical and functional performance indices (P_P and P_F) for different components of each system of the subway network are assessed through the SUPER model. Not only are the condition and safety assessed independently, but also both are integrated into a single performance index, the integrated performance index (P_I). Using a Weibull cumulative reliability-based function, a performance model is constructed for each component. An Ideal Performance Curve is developed and updated depending on the available inspection reports. A Predicted Performance Curve is developed for each component. A performance model is developed for each system independently (stations, tunnels and auxiliary structures). System performance models combine the performance of different components using series and parallel systems reliability. The performance of different systems in each line are also combined using a series/parallel modeling technique in order to develop the line performance model. Finally, the network performance model considers the performance of all lines of subway network.

It should be stressed that the SUPER model Predicted Performance Curve (PPC) has many advantages to other methods (markov chain, regression and reliability-based models). The PPC can be constructed using at least one inspection point; hence it does not need a big number of data points. It can be updated easily with every new inspection. In addition, the PPC can include the M&R action easily. Also, it does not require complex and difficult mathematical calculation. Finally it is the best profile that represents concrete deterioration.

The SUPER model is the first performance model that assesses structural performance of different components in a subway network and develops performance models for components, systems (stations, tunnels and auxiliary structures), lines and the entire network. The developed model is easy to implement, does not require much historical data and can easily handle the complexity of subway components, systems and network. The model is not mathematically hard to understand or apply, thus making it easy for transit managers to implement. The SUPER model is integral since it considers both safety and condition of the network. Finally, the developed model is generic since it can be used for any subway network worldwide.

CHAPTER 4: DATA COLLECTION

4.1 INTRODUCTION

As explained in the previous chapter, the developed SUPER model is based on vital data, which primarily comprises the model inputs. These required data consist of two main categories:

1. Historical inspection reports for stations, tunnels and auxiliary structures.
2. Weights of the functional and physical performance indices, in addition to the weights of the different structural defects and cracks. These weights are evaluated using the Analytic Hierarchy Process (AHP) method. In order to apply the AHP calculation, comparison matrices are developed. The comparison matrices are prepared, distributed and collected via a questionnaire.

Two types of data collection techniques are used in this research. The first technique is *direct data retrieval, filtering and sorting*. The second technique is a *questionnaire*. The first technique is used in order to gather the first category of data, which consists of information, retrieved from past inspection reports. Thus, past inspection reports are required for stations, tunnels and auxiliary structures. The inspection reports were provided by the *Société de Transport de Montréal* (STM) rehabilitation team (engineering unit) and the M&R reports were provided by the STM planning unit. The second category of data is gathered using a questionnaire (the second technique). This questionnaire is needed to fill-in the comparison matrices for structural cracks, defects and performance indices. A sample of this questionnaire is found in Appendix A. The questionnaires are sent to practitioners in subway stations (engineers, inspectors and managers) and experienced structural engineers.

4.2 INSPECTION REPORTS

The *Société de Transport de Montréal* (STM) provided the research with past inspection reports for stations, tunnels, and auxiliary structures. The main problem in the STM inspection reports (this is a general problem with most transit authorities) is the lack of complete reports for stations, tunnels and auxiliary structures of subway networks. Hence, the inspection history does not record regular inspections, nor complete ones for the entire network. Inspections were carried out in 1992, 1996, 1997, 1998, 2002, 2004 and 2005. However, not all stations, tunnels and auxiliary structures were inspected in each of these years. For a few structural systems, two inspection reports were found; some have only one and many of them have none. The reason behind the irregularities and the scarcity is that regular inspections are expensive and dangerous. These observations substantiate the strength of the SUPER model, which lies in using an ideal performance curve where no inspection report is found and using predicted (updated) performance curves where one or more inspection reports are available. Therefore, the irregularity of inspection history is not a constraint for developing performance curves in the SUPER model methodology.

Data are retrieved from inspection reports, filtered, and finally sorted in order to be ready for analysis and model development. The data retrieved from the different inspection reports are:

1. Year of construction of each structure,
2. Year of inspection of each structure,
3. Type of component: stair, wall, slab, dome, etc...
4. Location of component: external, internal.
5. Level of component: Level 0, 1, 2, etc...
6. Types of cracks/defects: EFFL, SHC, etc...
7. CME (to be used for P_P calculation) for structural defects.
8. CPE (to be used for P_F calculation) for the structural cracks.
9. M&R actions, improvements and year of action.

The retrieved information is filtered where for each station; for example, the year of construction, years of inspection, the types of defects and/or cracks, and then the type of component and its location are recorded. Filtered information is then sorted by inspection year for each station, tunnel and auxiliary structure. Additional sorting is also done using floor level. Then, sorting by the type and location of the component is done. Finally, sorting by the crack/defect type is performed. The inspection report data are filtered and sorted in 'Excel' spreadsheet files. A sample 'Excel' spreadsheet for the stations is presented in Table 4.1.

Analyzing the collected data from inspection reports, it is apparent that not all types of cracks and defects appear in the structural components. Table 4.2 shows the count of the cracks and defects in the different types of systems.

Table 4.1 Sample Station Inspection Report Data

Station	Year of Inspection	Year of Construction	Level	Element	Defect	CME	E/I
Champs-de-Mars	2005	1966	1	Wall	C	1	I
Champs-de-Mars	2005	1966	2	Top Slab	C	1	E
Champs-de-Mars	2005	1966	1	Wall	AAR	3	I
Champs-de-Mars	2005	1966	1	Wall	CJ	1	I
Champs-de-Mars	1997	1966	2	Wall	RCOR	4	I
Champs-de-Mars	1997	1966	1	Stair	C	3	E
Beaudry	1992	1966	1	Slab	DEL	3	E
Beaudry	1997	1966	3	Slab	C	5	E
Beaudry	2005	1966	1	Wall	DEL	5	I
Cote-Ste-Catherine	1996	1982	1	Wall	EFFL	4	I
Cote-Ste-Catherine	1996	1982	2	Top Slab	C	1	I
Cote-Vertu	1996	1986	1	Slab	C	3	I
Cote-Vertu	1996	1986	2	Top Slab	C	2	I
Cote-Vertu	1996	1986	2	Top Slab	EFFL	4	I
Cote-Vertu	1996	1986	1	Wall	EFFL	4	I
Du College	1996	1984	1	Wall	HCC	4	E
Du College	1996	1984	1	Wall	C	2	E
Du College	1996	1984	1	Slab	EFFL	4	E
Du College	1996	1984	2	Top Slab	STAL	4	E
Henri-Bourassa	2005	1966	4	Top Slab	ER	2	E
Henri-Bourassa	2005	1966	4	Top Slab	EFFL	3	E
Henri-Bourassa	2005	1966	4	Wall	SWE	2	E
Henri-Bourassa	2005	1966	4	Wall	C	2	I
Jean-Drapeau	2005	1967	1	Wall	INC	4	I
Jean-Drapeau	2005	1967	1	Wall	SEGR	4	I
Pie IX	2004	1976	2	Wall	DEL	2	I
Sherbrooke	2005	1966	2	Wall	CJ	3	E
Sherbrooke	2005	1966	2	Wall	C	2	E

Table 4.2 Cracks and Defects Count per System

	Cracks/Defects	Count per System		
		Stations	Tunnels	Auxiliary Structures
Cracks	SM	-	-	-
	CM	4	-	-
	FD	6	-	-
	SHC	3	-	3
	V	1	-	-
	W	25	-	2
	JC	1	-	-
	VMJ	-	-	-
	HMJ	-	-	-
Defects	C	1029	20	16
	EFFL	406	13	5
	SEGR	15	-	-
	SCA	3	-	-
	ER	16	-	-
	CJ	3	11	3
	HCC	9	2	-
	ABR	-	-	-
	RCOR	22	5	-
	DEL	62	18	5
	SWE	14	2	-
	DIS	1	-	-
	STAL	12	2	-
	INC	5	2	-
	AAR	1	-	-
	STRAT	1	-	-

For instance, '*cracks*' (secondary cracks) defect appear 1029 times in twelve stations (the highest), and found in almost all components. This is natural, since secondary *'cracks'* are the first type of defect that appears on structural components. Main causes of these cracks are diverse and can occur at the corners of doors and windows and other openings. It can be due to small water infiltration or due to shrinkage. However, these cracks do not affect structural integrity. The majority of defect scores for '*cracks*' is 0.2 and 0.4, (i.e. critical or on the threshold). Figure 4.1 shows the histogram and fitted Probability Distribution Function (PDF) of structural defect for *cracks*' normalized scores available in the stations. Although the normalized scores for *'cracks'* are counted as discrete numbers (either 0.4, or 0.6), statistically they can be assumed to follow a continuous distribution (i.e. a '*crack'* defect of 0.5 can happen). However, the histogram and PDF of the '*cracks'* defect do not successfully follow a normal distribution (i.e. the normality test fails). As a matter of fact, it does not have to be normal, because structural '*cracks*' defect depends on the external environment that the structural component is exposed to, which differs greatly from one place, one level, and from one system to another. The mean value of *'cracks'* defect scores is 0.45, (i.e. the performance relative to *'cracks'* is low). However the standard deviation is 0.21, which means that most of the values are between 0.24 and 0.66.

The second highest count of defect types is the *'efflorescence'* structural defect. Although it is not probably the most important defect, (it does not affect the integrity of the structure), it is found 474 times. *'Efflorescence'* defects appear as white deposits and stains due to migration of moisture salt from interior to exterior surface. It is noted that most efflorescence is seen in the upper floor of the stations, hence near the entrance where higher concentration of salts and excessive moister exist. Figure 4.2 shows the histogram and the fitted Probability Distribution Function (PDF) of the *'efflorescence'* structural defect normalized scores in the stations. Figure 4.2 shows that most of the performance values (P_P) of *'efflorescence'* are equal to 0.8, i.e. not critical. The mean value is 0.76 or rounded to 0.8; whereas the standard deviation is extremely small, equal to 0.078. Here also, the fitted distribution does not successfully follow a normal curve (The normality test fails).

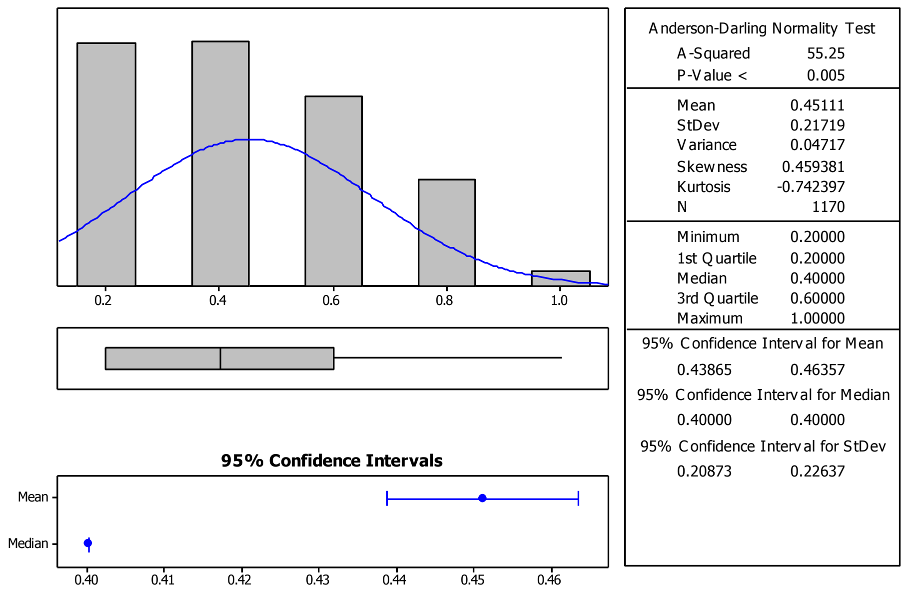


Figure 4.1 '*Cracks*' Defect Normalized Scores Histogram and PDF

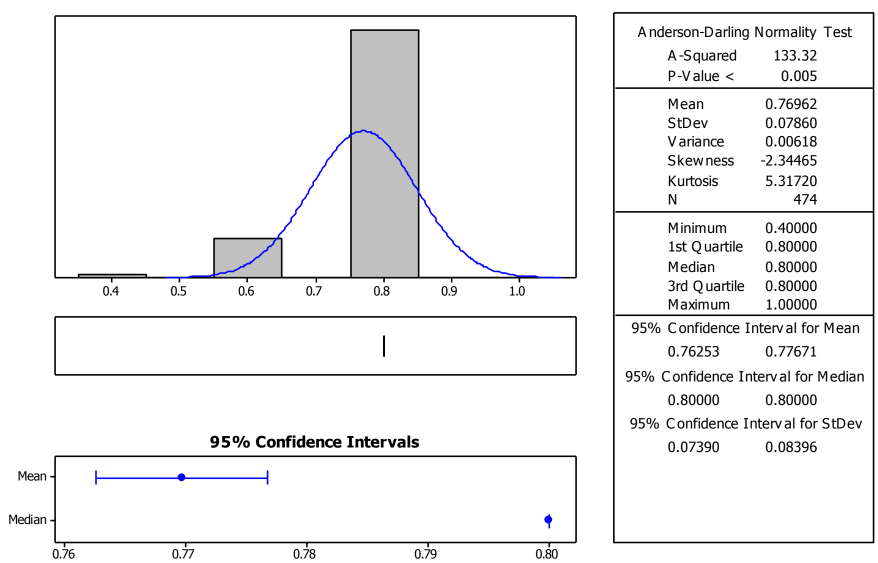


Figure 4.2 *'Efflorescence'* Defect Normalized Scores Histogram and PDF

With reference to Table 4.2, it can be seen that almost all types of defects and cracks are found in stations in comparison to tunnels and auxiliary structures. It is observed that the SM, VMJ and HMJ are not present is the collected inspection reports. In addition to that, no cracks are found in the tunnels inspection reports. Figure 4.3 illustrates a pie-chart of the distribution of both the cracks and defects in the systems.

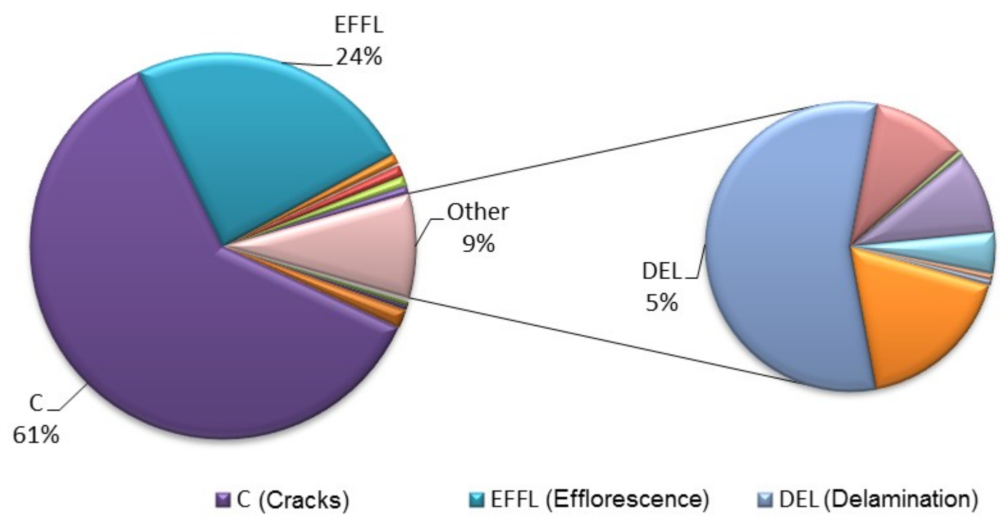


Figure 4.3 Cracks and Defects Distribution in Systems

It is observed that in the inspection reports provided by the STM, important structural cracks are rarely found. For instance ‘Shear Crack’ is found six times only, ‘Flexural Deformation’ is found six times, and ‘Continued Movement’ four times. ‘Cracks’ (C) form 61% of the total cracks and defects in the system, ‘efflorescence’ form 24% (EFFL), and the remaining cracks and defects (‘*others*’) form 9% only (out of this 9%, ‘delamination’ (DEL) is 5%). Thus, the defects are the dominant deficiencies in the collected systems inspection reports. This last observation is important, since it confirms the satisfactory structural design and construction practice performed in the STM network. However, it is evident that harsh the external environment greatly affects the structure. It should be stressed that the high number of defects compared to cracks does not mean that the structures are not deteriorated, since defects and cracks do not share the same weight.

It is also interesting to look at the distribution of the cracks and defects per level of station. Table 4.3 shows the count of the cracks and defects per level of stations, and Figure 4.4 illustrates the respective distribution per level.

Table 4.3 Cracks and Defects Count per Level in Stations

	Count per Level in Stations					
Level	0	1	2	3	4	5
Cracks	3	11	8	15	3	-
Defects	58	653	468	314	105	1

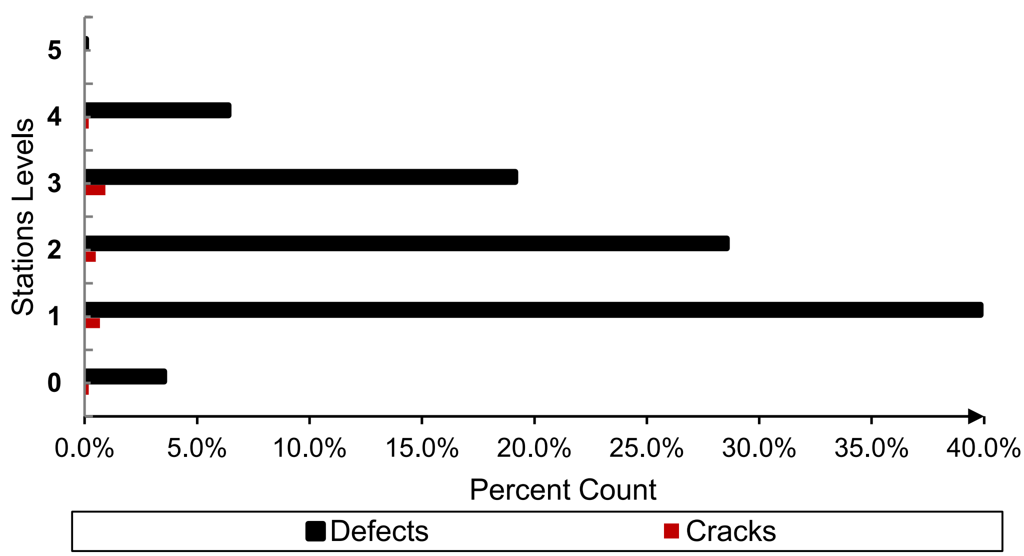


Figure 4.4 Cracks and Defects Distribution per Level in Stations

It is observed that the highest number of defects is found in the first level and it decreases when going up. However, the cracks do not follow this distribution, but they are more or less equally distributed over the intermediary floors. The distribution of cracks and defects per type of component in each system is also shown. Table 4.4 shows the count of the cracks and defects per component in the systems.

Table 4.4 Cracks and Defects Count per Component of Systems

	Count per Component of Systems							
System	Stations			Tunnels			Auxiliary Structures	
Component	Walls	Slabs	Stairs	Domes	Walls	Bottom Slab	Walls	Slabs
Cracks	16	23	1	-	-	-	4	1
Defects	957	621	21	44	31	-	24	5

It can be seen that the highest number of defects and cracks is found in the walls and slabs of the stations. The bottom slab of the tunnels does not have any defect or cracks, and the most probable explanation here is that it has not been inspected. Finally, the distribution of the cracks and defects per year of construction of the system is analyzed. Table 4.5 shows the count of the defects and cracks per year of construction, while Figure 4.5 illustrates the distribution of the total cracks and defects per year of construction.

Table 4.5 Cracks and Defects Count per Year of Construction

		Count per Year of Construction								
Year of Construction		1966	1967	1976	1978	1982	1984	1986	1987	1988
Stations	Cracks	28	1	2	7	-	1	-	1	
	Defects	437	24	183	288	199	192	162	114	
Tunnels	Cracks	-			-					
	Defects	56			19					
Auxiliary Structures	Cracks	5								-
	Defects	12								17

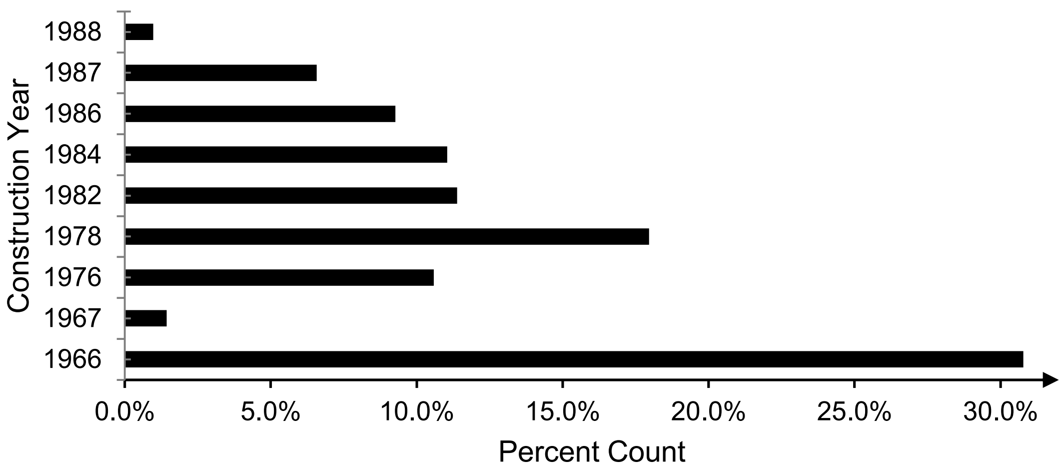


Figure 4.5 Cracks and Defects Distribution per Year of Construction

It is observed that the systems constructed in year 1966 are the most deficient, and the number of the cracks and defects decreases with the increase on the year of construction. This is natural, since the oldest systems must be the most deteriorated.

4.3 QUESTIONNAIRES

The second category of data needed for the SUPER model is the weights of cracks and defects in addition to the weights of performance indices. The weights are calculated using the Analytic Hierarchy Process (AHP) methodology. However, the AHP requires filling comparison matrices among the different cracks/defects/indices. Filling the matrices is done via a *questionnaire*, which is distributed to senior structural engineers at STM and major engineering firms with an infrastructure design and rehabilitation specialization.

A sample questionnaire is found in Appendix A. Ninety (90) questionnaires were distributed where only thirty two (32) were gathered. Out of these thirty two (32), only nine (9) were from the STM, which comprises 28% in this category of data (approximately the third). The remaining questionnaires were collected from engineering design firms in Canada and USA. The targeted respondents were transit managers and engineers dealing with the maintenance of subway networks, such as STM, and experienced structural engineers, such as engineering firms. The average year of experience of the respondents is fourteen (14). The low number of STM answers is due to the fact that STM is not a design firm, thus few experienced structural engineers are employed. This questionnaire was of interest to the structural engineers in the design and rehabilitation of infrastructure departments (i.e. engineering firms). The respondents can be divided into three categories, depending on the main expertise: STM managers, structural designers, and structural rehabilitation engineers. Table 4.6 shows the number of responses per category. The structural engineers' total responses are twenty-three (23) out of these sixteen (16) are structural designers and only seven (7) are structural rehabilitation engineers. The low number of rehabilitation engineers is related to the low number of these experts in the engineering industry.

Table 4.6 Categories of Questionnaires Respondents

Category of Respondents	No. of Questionnaires
STM Managers	9
Structural Designers	16
Structural Rehabilitation Engineers	7

The questionnaire consists of four parts. Part I gathers personal information of respondents, such as name, title and years of experience. Part II consists of asking the participants to fill-in the comparison matrices of structural cracks according to their categories. In this part, structural cracks belong to either design-based or construction-based causes. Hence, in Part II.A, the participant is asked to compare the design-based crack category to construction-based crack category. Then, in Part II.B, the participant is asked to compare the different design-based cracks among themselves in pairs, i.e. pair-wise comparison. Finally, in Part II.C, the participant is asked to relatively compare different construction-based cracks among themselves.

Part III deals with asking the participants to fill-in the comparison matrices of structural defects according to their categories. In this part, structural defects belong to either chemical-based or mechanical-based deficiencies. Hence, in Part III, a procedure similar to that in part II was used. The last part of the questionnaire, Part IV, the comparison is done between the functional performance index (P_F) and the physical performance index (P_P). Figure 4.6 shows the distribution of the questionnaire responses per category. The STM form 28% of the responses, while structural designers form 50% (the majority) and 22% are structural rehabilitation engineers.

Looking at the importance scores per category of respondents, it is observed that structural engineers preferred design-based cracks to construction-based cracks, and chemical-based defects to mechanical-based defects. In addition, the structural engineers emphasized that shrinkage cracks defects and the corrosion related defects are the most important ones. This is true, because the designers have the functionality in the background when assigning importance scores. On the contrary, the structural rehabilitation engineers' concern is the inspection and the maintenance of the structure, thus they emphasize the construction-based category of cracks, and the mechanical-based category of defects.

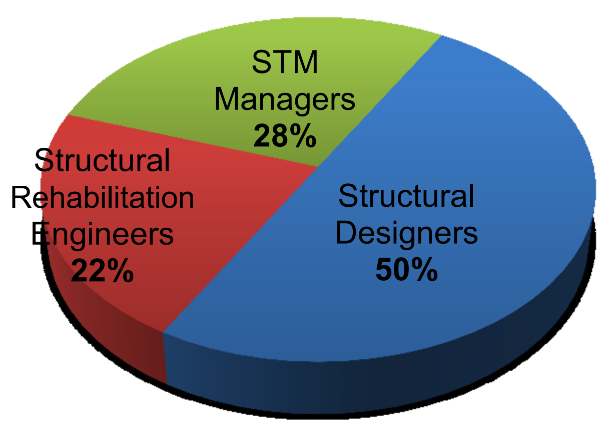


Figure 4.6 Distributions of Respondents Categories

4.4 SUMMARY

This chapter covers the data collection techniques used in this research. Two techniques were used: *direct data retrieval* and *questionnaire*. Scattered and incomplete inspection reports were provided by the STM. The data required for the SUPER model were retrieved, filtered and sorted using Excel files. Replies to the questionnaire formed 35.5% of the total number sent to experts.

CHAPTER 5: THE SUPER MODEL IMPLEMENTATION: RESULTS AND ANALYSIS

5.1 INTRODUCTION

Figure 5.1 illustrates the outline of chapter 5. After this introduction, the chapter starts (section 5.2) by evaluating the weights of cracks, defects and performance indices using the Analytic Hierarchy Process (AHP) analysis for the collected data using questionnaires. In section 5.3, the SUPER model implementation is presented. It is also implemented to a case study from a segment 'STM Sub-Network' of STM network in order to prove its functionality.

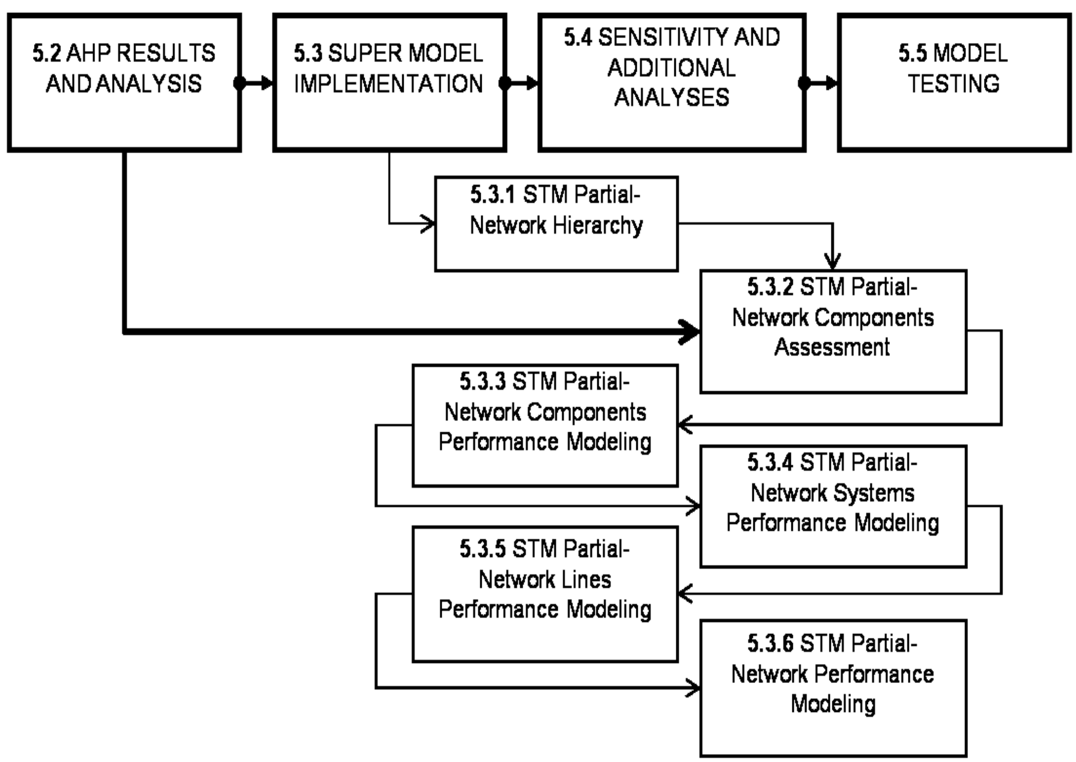


Figure 5.1 Outline of Chapter 5

First, the STM sub-network hierarchy is defined in which different components of performance assessment is performed. Performance curves of different components, systems, lines, and sub-network are constructed. In addition to the case study, sensitivity analyses are performed in section 5.4. The effect of changing various inputs, such as construction year, weights of performance indices, and scores of cracks and defects, are analyzed. Finally. Section 5.5 presents the testing and analysis processes of SUPER model.

5.2 AHP RESULTS AND ANALYSIS

The weights of cracks, defects and performance indices are evaluated using the Analytic Hierarchy Process (AHP). The research has collected thirty two (32) questionnaires of the AHP pair-wise comparison matrices to assess the weights of various factors, cracks, and defects. The following sub-sections present the obtained average weights using AHP.

5.2.1 Structural Cracks Weights

The structural cracks are divided into two categories: design-based and construction based cracks. An average weight of each category is calculated, and tabulated in Table 5.1.

Table 5.1 Structural Cracks Categories Weights

Structural Cracks Categories	Average Weight
Design-based	67%
Construction-based	33%

The two categories of structural cracks are not equal in importance. The design-based cracks category is two times more important than the construction-based cracks category. It should stressed that this result is not shared by all experts. Lot of structural experts considers design-based cracks more important than the construction-based cracks, but on the other hand other experts consider exactly the contrary. Thus, further research and questionnaires must be performed before clarifying this particular point. The average structural cracks weights under each category are calculated and tabulated in Tables 5.2 and 5.3, respectively.

Table 5.2 Design-Based Structural Cracks Weights

Structural Cracks Identification	**Structural Cracks Description**	**Average Weight**
SM	Stable Movement	4.04%
CM	Continued Movement	32.10%
FD	Flexural Deformation	20.31%
SHC	Shear Crack	28.04%
V	Vibration	15.61%

Table 5.3 Construction-Based Structural Cracks Weights

Structural Cracks Identification	**Structural Cracks Description**	**Average Weight**
W	Water Infiltration	23.85%
JC	Joint Crack	29.61%
VMJ	Vertical Misalignment	23.55%
HMJ	Horizontal Misalignment	22.73%

Multiplying each crack weight by its respective category weight, the global crack weight is evaluated. Table 5.4 shows the average global weight of the structural cracks. It shows that *'continued movement'* is the most important structural crack with a 21.51% weight, followed by the '*shear crack'* with an 18.79% weight. *'Flexural deformation'* comes next with a 13.61% weight. *Vibration ', 'water infiltration ', 'joint crack ', 'vertical misalignment* and '*horizontal misalignment'* have almost the same weight. Finally, *'stable movement'* is the least important crack. When *'continued movement'* is recorded in a structural component, this means that the component fails to resist the applied loads and has surpassed the elastic behavior zone. Whereas *'shear crack'* is very critical since it can result in a sudden failure. *'Flexural deformation'* is less critical because rebar can yield and no sudden failure will happen.

Table 5.4 – Structural Cracks Global Weights

Structural Cracks Identification	**Structural Cracks Description**	**Average Global Weight**
SM	Stable Movement	2.71%
CM	Continued Movement	21.51%
FD	Flexural Deformation	13.61%
SHC	Shear Crack	18.79%
V	Vibration	10.46%
W	Water Infiltration	7.87%
JC	Joint Crack	9.77%
VMJ	Vertical Misalignment	7.77%
HMJ	Horizontal Misalignment	7.50%

5.2.2 Structural Defects Weights

The same analysis is repeated for the structural defects. The structural defects are divided into two categories: chemical-based and mechanical-based defects. First of all, an average weight of each category is calculated and tabulated in Table 5.5.

Table 5.5 Structural Defects Categories Weights

Structural Defects Categories	Average Weight
Chemical-based	53.7%
Mechanical-based	46.3%

The two categories of structural defects show a small difference in weight. The average defects weights under each category are calculated and tabulated in Tables 5.6 and 5.7 respectively.

Table 5.6 Chemical-Based Structural Defects Weights

Structural Defect Identification	Structural Defect Description	Average Weight
RCOR	Rebar Corrosion	27.84%
DEL	Delamination	10.47%
SWE	Sweating	4.51%
DIS	Disintegration	17.11%
STAL	Stalactite	9.48%
INC	Incrustation	8.55%
AAR	Alkali-Aggregate-Reaction	12.77%
STRAT	Stratification	9.20%

Table 5.7 Mechanical-Based Structural Defects Weights

Structural Defect Identification	**Structural Defect Description**	**Average Weight**
C	Cracks	24.62%
EFFL	Efflorescence	20.15%
SEGR	Segregation	12.35%
SCA	Scaling	10.78%
ER	Erosion	8.51%
CJ	Construction Joint	6.31%
HCC	Honey Comb Cracks	9.33%
ABR	Abrasion	8.03%

Multiplying each defect weight by its respective category weight, the global defect weight is evaluated. Table 5.8 shows the average global weight of the structural defects. Analyzing the global defect weights, the *'rebar corrosion'* defect is the most important one and thus affects the structural physical performance. The *'cracks'* (or secondary cracks) follows next in importance. It should be noted that *'efflorescence'* and *'disintegration'* have approximately the same importance weight. Finally, the remaining defects show small weights. Comparing the defects is difficult and involves subjectivity. Most of the defects, apart from some well known ones (*cracks, rebar corrosion, and disintegration*), seem to be similar when assessing their damage to the physical condition of a component. This explains why most of these defects have the same low weight. It can be concluded that most of these defects can be grouped into one set and analyzed together, and do not affect the total performance of the component.

Table 5.8 Structural Defects Global Weights

Structural Defect Identification	Structural Defect Description	Average Global Weight
RCOR	Rebar Corrosion	14.95%
DEL	Delamination	5.62%
SWE	Sweating	2.42%
DIS	Disintegration	9.19%
STAL	Stalactite	5.09%
INC	Incrustation	4.59%
AAR	Alkali-Aggregate-Reaction	6.86%
STRAT	Stratification	4.94%
C	Cracks	11.40%
EFFL	Efflorescence	9.33%
SEGR	Segregation	5.72%
SCA	Scaling	4.99%
ER	Erosion	3.94%
CJ	Construction Joint	2.92%
HCC	Honey Comb Cracks	4.32%
ABR	Abrasion	3.72%

5.2.3 Performance Indices Weights

The questionnaire also compares the functional performance index (P_F) to the physical performance index (P_P). Table 5.9 shows the weight of each performance index using AHP analysis. The P_F and P_P have weights of 74%, and 26%, respectively. This result is expected since it confirms common sense and basic knowledge of structural engineering.

Table 5.9 Performance Indices Weights

Structural Performance Indices	Average Weight
Functional Performance Index	74%
Physical Performance Index	26%

5.2.4 Statistical Analysis of Cracks and Defects Weights

The calculated weights by the AHP method in the previous sections are the average (mean) values from thirty-two (32) questionnaires. However it is important to analyze some major statistical figures concerning these weights, such as the standard deviation, minimum and maximum values, and the values for a 95% confidence level. These statistical figures are necessary in order to analyze if the average weights can be used with a certain confidence and in order to check if there is significant deviation from the average values. Tables 5.10 and 5.11 show the statistical analysis for the cracks' weights and the defects' weights, respectively.

Table 5.10 Cracks' Weights Statistical Analysis Results

Cracks	Mean	Standard Deviation	Minimum	Maximum	95% Confidence Level	
					Lower Bound	Upper Bound
SM	2.71%	1.59%	1.7%	10.1%	2.21%	3.35%
CM	21.51%	8.72%	7.6%	43.3%	17.75%	24.04%
FD	13.61%	2.66%	5.4%	18.3%	7.57%	9.49%
SHC	18.79%	4.79%	6.3%	28.4%	14.4%	17.86%
V	10.46%	1.84%	3.2%	12.5%	7.02%	8.35%
W	7.87%	4.44%	0.9%	17.1%	5.57%	8.77%
JC	9.77%	4.91%	1.8%	23.6%	11.4%	14.95%
VMJ	7.77%	4.19%	2.3%	17.8%	10.9%	13.93%
HMJ	7.5%	4.59%	2.1%	17.7%	9.26%	12.57%

Table 5.11 Defects' Weights Statistical Analysis Results

Defects	Mean	Standard Deviation	Minimum	Maximum	95% Confidence Level	
					Lower Bound	Upper Bound
C	11.4%	6.46%	2.9%	40.7%	8.7%	13.37%
EFFL	9.33%	3.88%	0.6%	13.3%	7.74%	10.54%
SEGR	5.72%	3.3%	0.4%	15.9%	3.72%	6.09%
SCA	4.99%	1.92%	0.6%	8.3%	3.25%	4.64%
ER	3.94%	1.17%	0.7%	6.1%	2.58%	3.43%
CJ	2.92%	1.68%	0.6%	7.3%	2.5%	3.75%
HCC	4.32%	2.13%	0.5%	6.9%	4.22%	5.76%
ABR	3.72%	1.54%	0.3%	6.1%	2.83%	3.94%
RCOR	14.95%	7.00%	3.9%	43.9%	11.98%	17.03%
DEL	5.62%	4.92%	1.7%	18.2%	4.78%	8.33%
SWE	2.42%	4.85%	0.7%	18.7%	1.97%	5.47%
DIS	9.19%	5.50%	4.2%	34.5%	7.53%	11.50%
STAL	5.09%	3.98%	1.6%	18.2%	3.13%	6.01%
INC	4.59%	3.75%	1.5%	18.2%	4.2%	6.91%
AAR	6.86%	5.13%	2.1%	27.1%	4.42%	8.12%
STRAT	4.94%	3.94%	1.4%	18.2%	4.47%	7.32%

Looking at Tables 5.10 and 5.11, it can be seen that there is a considerable deviation between the mean value and the minimum and maximum values. The extreme minimum and maximum values show a discrepancy in the importance consideration of the cracks and defects' weights. Also, the standard deviation of some of the cracks and defects is large. However, the standard deviation for defects is higher than that of the cracks. These observations are due to the fact that the respondents are not all homogeneous in thinking and judgment. With reference to chapter 4 (data collection chapter), the respondents form three different groups with different background.

Regardless of the non-homogeneity of the weights, the 95% confidence level ranges are not far from the mean values of the cracks and defects' weights. Thus, the weights may vary within a certain range with a 95% confidence. In general, the 95% confidence range varies between -40% and +40% of the mean value. Thus, a sensitivity analysis is required, in order to check if the integrated performance index and hence the performance curve changes with the alteration of cracks and defects' weights between -40% and +40%. Such an analysis is done later in this chapter.

5.3 SUPER MODEL IMPLEMENTATION

A segment of STM network is chosen for the SUPER model implementation (called in this case study *'STM Sub-Network'*) since no inspection reports are found for the complete network structures. The application of the SUPER model to the STM Sub-Network aims at showing the functionality of the new model to any subway network. Table 5.12 shows the different lines, systems, and construction and inspection years of the Sub-Network. The STM Sub-Network lies in the center of the STM network. The STM Sub-Network selection depends on the following criteria: (i) Orange and Green lines are the oldest lines in the STM network, constructed in 1966; (ii) Inspection reports are available for almost all the oldest systems of the STM network. Newly constructed systems are less probable to have inspection reports for them; (iii) 'Berri UQAM' station is connected to three lines: the Green, Orange and Yellow lines; (iv) 'Berri UQAM' and Saint Laurent stations are two of the most used stations; and (v) 'Beaudry' station is the only station that has three inspection reports. In addition to the all of the above, selecting the STM Sub-Network specifically depends on subjective judgement as well.

Table 5.12 STM Sub-Network Identification Table

Line	*Systems Name*	Systems Designation	Construction Year	Inspection Years	M&R Year
Orange	*Sherbrooke*	**STA 1**	1966	2005	2005
	PV Sherbrooke	**AS 1**	1966	1995	-
	Sherbrooke – Berri UQAM	**TUN 1**	1966	2004	-
	Berri UQAM	**STA 2**	1966	-	2005
	PV Viger	**AS 2**	1966	-	-
	Berri UQAM – Champs de Mars	**TUN 2**	1966	2004	-
	Champs de Mars	**STA 3**	1966	2005, 1997	2005
	PVM St Dominique	**AS 3**	1966	-	-
	Champs de Mars – Place d'Armes	**TUN 3**	1966	2004	-
Green	*Beaudry*	**STA 4**	1966	2005, 1997, 1992	2005
	PR Plessis	**AS 4**	1966	1995	-
	Beaudry – Berri UQAM	**TUN 4**	1966	2004	-
	Saint Laurent	**STA 5**	1966	2005	2005
	PV Clark	**AS 5**	1966	-	-
	Berri UQAM – Saint Laurent	**TUN 5**	1966	2004	-
Yellow	*Jean Drapeau*	**STA 6**	1966	2005	2005
	PV Bonsecours	**AS 6**	1966	-	-
	Berri UQAM – Jean Drapeau	**TUN 6**	1966	-	-

It should be noted that 'Berri UQAM' station might be considered a system either on the Orange line or on the Green line. In this research case study, 'Berri

UQAM' station is considered a station on the Orange line, since according to STM, the number of users of the Orange line is higher than the number of users of the Green line using this particular station. Figure 5.2 illustrates the STM Sub-Network layout, indicating all systems on each line.

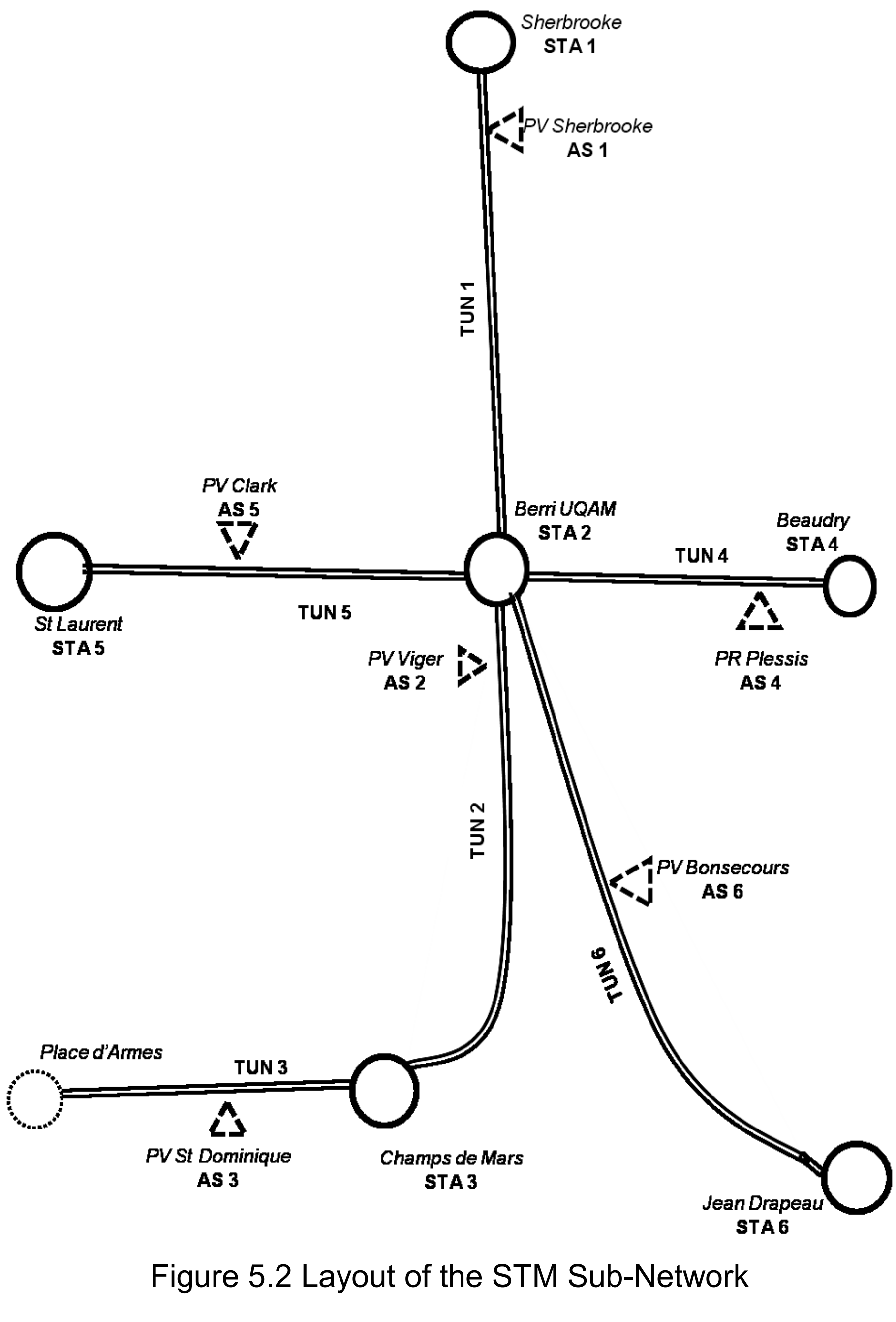


Figure 5.2 Layout of the STM Sub-Network

Referring to Table 5.10 and Figure 5.2, this STM Sub-Network consists of three lines and eighteen systems: STA1 to STA6, TUN1 to TUN6 and AS1 to AS6. All systems are constructed in 1966, thus according to the SUPER model, the expected service life is 1966 + 100 years = 2066 (refer to Chapter 3).

It is important to state that the improvement under the Maintenance and Rehabilitation or repair (M&R) actions is difficult to assess from the inspection reports. Furthermore, it is impossible to assign in each report which M&R action improves which components. Therefore, the SUPER model implementation to the STM Sub-Network assumes that the M&R action is done on the system (particularly stations) improving the overall system integrated performance to up to 90% of the total performance, i.e. to $P_I = 0.9$. Furthermore, the remaining service life (after M&R) is considered 90 years (proportional to 90 / 100 = 0.9) and not 100 years. Furthermore, if no inspection report is found after the M&R action, it is assumed that the Ideal Performance Curve (IPC) applies one year after the M&R action. In 2005, a large Maintenance and Repair (M&R) project was performed to the oldest STM stations only entitled 'Reno-Stations II'. Twenty-four (24) stations, constructed in 1966, were part of the project (refer to literature review, chapter 2).

5.3.1 STM Sub-Network Hierarchy

The starting point of the SUPER model is to develop the network hierarchy. The STM Sub-Network hierarchy is defined in Figure 5.3. The STM Sub-Network consists of the 'Orange', 'Green', and 'Yellow' lines. The 'Orange' line consists of nine systems: STA1, TUN1, AS1, STA2, TUN2, AS2, STA3, TUN3, and AS1.

The ‘Green’ line consists of six systems: STA4, TUN4, AS4, STA5, TUN5, and AS5. While the ‘Yellow’ line consists of three systems: STA6, TUN6, and AS6.

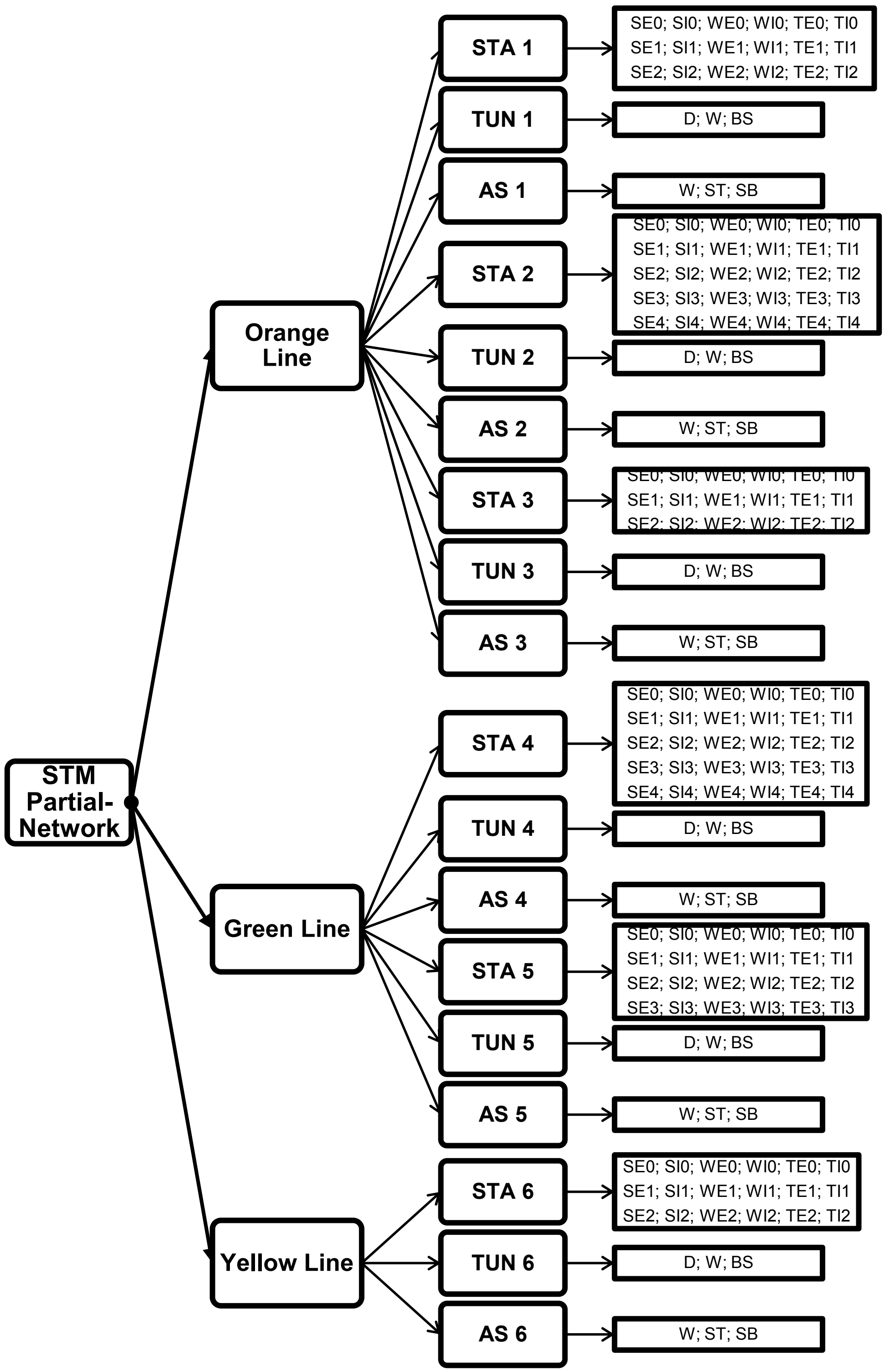


Figure 5.3 STM Sub-Network Hierarchy

From here on, the systems are designated according to their nomenclature and not the real name. References to the real names are done in special cases only. Stations STA1, STA3 and STA6 consist of two floors (in addition to the train platform). Stations STA2 and STA4 consist of four floors. Station STA5 consists of three floors. The components are listed accordingly in Figure 5.3.

5.3.2 STM Sub-Network Components Performance Assessment

Depending on the hierarchy, the physical, functional and integrated performance indices of each component are evaluated (at each inspection year). The weights of the cracks, defects and performance indices are evaluated using AHP in the previous section. The cracks and defect scores are originally taken from the inspection reports, then obtained from the Excel files (refer to data collection, chapter 4) after being sorted. It should be noted that not all components are inspected. Thus, for a component that is not inspected, a score of 1.0 is assigned. The Functional Performance Index (P_F) is calculated using the equation developed in chapter 3, specifically Equation (3.4). On the other hand, the Physical Performance Index (P_P) is calculated using the equation developed in chapter 3, specifically Equation (3.8). Finally the Integrated Performance Index (P_I) is calculated using Equation (3.9).

5.3.2.1 Stations Components' Performance Assessment

The STM Sub-Network stations were inspected in 1992, 1997 and 2005. In fact, all of them were inspected and renovated in 2005, since they are part of the 'Reno-Station II' program. One special case is STA2, known to be inspected and even renovated in 2005, although the inspection report is lost. Hence, an M&R action applies in 2005. Table 5.11 shows the detailed performance assessment of STA1, for the 2005 inspection year. Table 5.13 is only a sample; the detailed components performance assessment tables for the rest of the stations are found in Appendix B. Table 5.13 shows that nothing is reported in the inspection for floor 0 (train platform floor), thus the P_P, P_F and P_I are equal to unity. However, there are lot of components that are inspected in floors 1 and 2. SE1, for instance, has been inspected, and its respective P_I in 2005 equals 0.93.

STA3 was inspected in 1997 and in 2005, and renovated in 2005. Very small deterioration was observed in 1999 and the station was not renovated. The components continued deteriorating until 2005. However, the decrease of performance between the year of construction in 1966 and the final inspection year in 2005 was not significant. Next, STA4 was inspected in 1992, 1997 and 2005. The performance assessments show that the components in 2005 are deteriorated considerably compared to 1992 and 1997. STA5 and STA6 components are both inspected and renovated in 2005. However, the reduction of performance in 2005 of the components of these two stations is not considerable.

Table 5.13 Station STA1 Components Detailed Performance Assessment

	Weight (W_S)	Score (S_S)																	
		Level 0						Level 1						Level 2					
		SE0	SI0	WE0	WI0	TE0	TI0	SE1	SI1	WE1	WI1	TE1	TI1	SE2	SI2	WE2	WI2	TE2	TI2
SM	2.71%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
CM	21.51%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
FD	13.61%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
SHC	18.79%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
V	10.46%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
W	7.87%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
JC	9.77%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
VMJ	7.77%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
HMJ	7.50%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
P_{Fi}	74.29%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
RCOR	14.95%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
C	11.40%	1.0	1.0	1.0	1.0	1.0	1.0	0.2	1.0	0.2	0.2	1.0	1.0	1.0	1.0	0.4	1.0	1.0	1.0
EFFL	9.33%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.4	1.0	1.0	1.0
SEGR	5.72%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
SCA	4.99%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
DEL	5.62%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
SWE	2.42%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.4	1.0	1.0	1.0
DIS	9.19%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
ER	3.94%	1.0	1.0	1.0	1.0	1.0	1.0	0.2	1.0	1.0	0.4	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
STAL	5.09%	1.0	1.0	1.0	1.0	1.0	1.0	0.6	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
INC	4.59%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
AAR	6.86%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
STRAT	4.94%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
CJ	2.92%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.4	1.0	1.0	1.0
HCC	4.32%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
ABR	3.72%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
P_{Pi}	25.71%	1.00	1.00	1.00	1.00	1.00	1.00	0.76	1.00	0.83	0.80	1.00	1.00	1.00	1.00	0.79	1.00	1.00	1.00
P_{Ii}	100.00%	1.00	1.00	1.00	1.00	1.00	1.00	0.93	1.00	0.95	0.95	1.00	1.00	1.00	1.00	0.94	1.00	1.00	1.00

5.3.2.2 Tunnels Components' Performance Assessment

The main and typical tunnel components are the sidewalls, bottom slabs and domes. Most of the tunnels were inspected in 2004, although no renovation was done. Table 5.14 shows the tunnel TUN1 components detailed performance assessment for the 2004 inspection. The detailed performance assessments for the remaining tunnel components are found in Appendix B. TUN2 to TUN5 were inspected in 2004, and they showed little deterioration. However, no inspection report is found at STM for the tunnel section below the Saint Lawrence River, i.e. the tunnel between 'Berri-UQAM' and 'Longeuil' stations. For this reason, the P_I of TUN6 components are equal to unity.

5.3.2.3 Auxiliary Structures Components' Performance Assessment

The main and typical auxiliary structure components are the sidewalls, top and bottom slabs. Most of the auxiliary structures were not inspected (AS2, AS3, AS5 and AS6), and no renovation was done. Only two auxiliary structures were inspected in 1995 (AS1 and AS4). It should be noted that the assessments of the inspected auxiliary structure components show little deterioration. Table 5.14 shows the AS1 auxiliary structure components detailed performance assessment as well. Refer to Appendix B for the detailed performance assessment of other auxiliary structures' components.

Table 5.14 Tunnel TUN1 and Auxiliary Structure AS1 Components Detailed Performance Assessment

TUN 1

	Weight (W_S)	Score (S_S)		
		DOME (D)	WALLS (W)	BOTTOM SLAB (BS)
SM	2.71%	1.0	1.0	1.0
CM	21.51%	1.0	1.0	1.0
FD	13.61%	1.0	1.0	1.0
SHC	18.79%	1.0	1.0	1.0
V	10.46%	1.0	1.0	1.0
W	7.87%	1.0	1.0	1.0
JC	9.77%	1.0	1.0	1.0
VMJ	7.77%	1.0	1.0	1.0
HMJ	7.50%	1.0	1.0	1.0
P_{Fi}	**74.29%**	**1.00**	**1.00**	**1.00**
RCOR	14.95%	1.0	1.0	1.0
C	11.40%	0.4	0.6	1.0
EFFL	9.33%	0.6	0.6	1.0
SEGR	5.72%	1.0	1.0	1.0
SCA	4.99%	1.0	1.0	1.0
DEL	5.62%	0.6	0.6	1.0
SWE	2.42%	1.0	1.0	1.0
DIS	9.19%	1.0	1.0	1.0
ER	3.94%	1.0	1.0	1.0
STAL	5.09%	1.0	1.0	1.0
INC	4.59%	1.0	1.0	1.0
AAR	6.86%	1.0	1.0	1.0
STRAT	4.94%	1.0	1.0	1.0
CJ	2.92%	0.4	0.6	1.0
HCC	4.32%	1.0	1.0	1.0
ABR	3.72%	1.0	1.0	1.0
P_{Pi}	**25.71%**	**0.84**	**0.89**	**1.00**
P_{Ii}	**100.00%**	**0.96**	**0.97**	**1.00**

AS 1

	Weight (w_S)	Score (S_S)		
		WALLS (W)	TOP SLAB (ST)	BOTTOM SLAB (SB)
SM	2.71%	1.0	1.0	1.0
CM	21.51%	1.0	1.0	1.0
FD	13.61%	1.0	1.0	1.0
SHC	18.79%	0.8	1.0	1.0
V	10.46%	1.0	1.0	1.0
W	7.87%	0.8	1.0	1.0
JC	9.77%	1.0	1.0	1.0
VMJ	7.77%	1.0	1.0	1.0
HMJ	7.50%	1.0	1.0	1.0
P_{Fi}	**74.29%**	**0.94**	**1.00**	**1.00**
RCOR	14.95%	1.0	1.0	1.0
C	11.40%	0.8	1.0	1.0
EFFL	9.33%	1.0	1.0	1.0
SEGR	5.72%	1.0	1.0	1.0
SCA	4.99%	1.0	1.0	1.0
DEL	5.62%	1.0	1.0	1.0
SWE	2.42%	1.0	1.0	1.0
DIS	9.19%	1.0	1.0	1.0
ER	3.94%	1.0	1.0	1.0
STAL	5.09%	1.0	1.0	1.0
INC	4.59%	1.0	1.0	1.0
AAR	6.86%	1.0	1.0	1.0
STRAT	4.94%	1.0	1.0	1.0
CJ	2.92%	1.0	1.0	1.0
HCC	4.32%	1.0	1.0	1.0
ABR	3.72%	1.0	1.0	1.0
P_{Pi}	**25.71%**	**0.97**	**1.00**	**1.00**
P_{Ii}	**100.00%**	**0.95**	**1.00**	**1.00**

5.3.3 STM Sub-Network Components Performance Modeling

The next step after the components performance assessment is the performance modeling. For every component in a specific system, an integrated performance curve is constructed. The components that were not inspected follow the Ideal Performance Curve (refer to Equation 3.17). The components that are inspected at least once follow an Updated Performance Curve (refer to Equation 3.20). The final update performance curve is considered the Predicted Performance Curve (refer to Equations 3.21 and 3.23). It should be noted that the M&R actions are assumed to act on the whole system (station, tunnel, or auxiliary structure) and not on the different components. However, this assumption is specific to this case study solely. Sample of some components performance curves of STA1, TUN1 and AS1 are illustrated in Figures 5.4, 5.5, and 5.6 respectively.

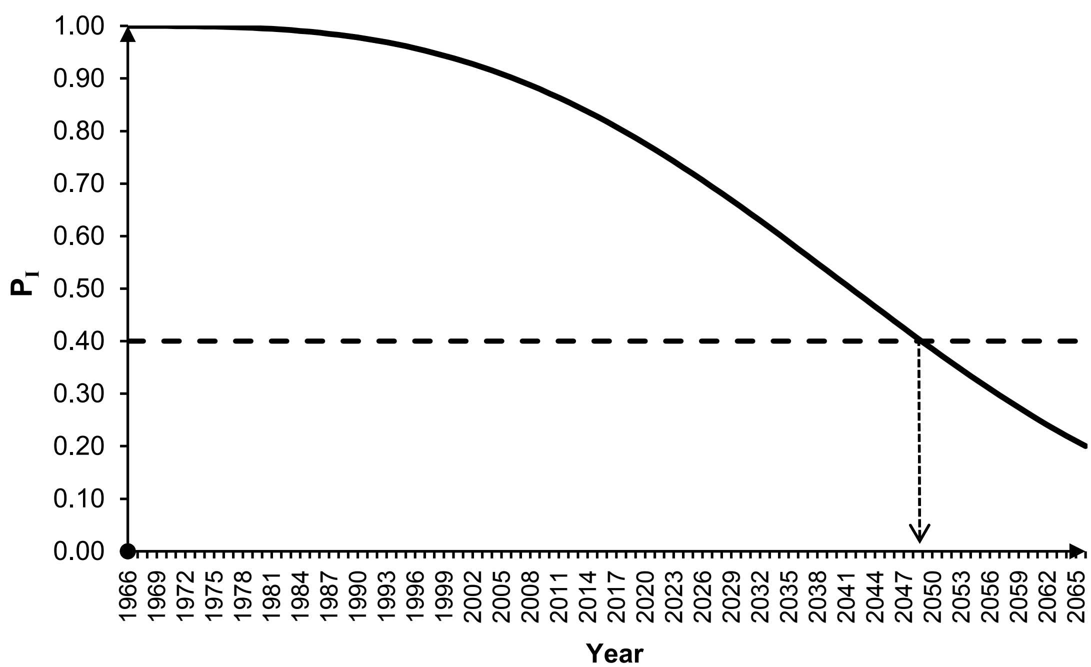


Figure 5.4 Interior Wall (WI2) Component of STA1 Performance Curve

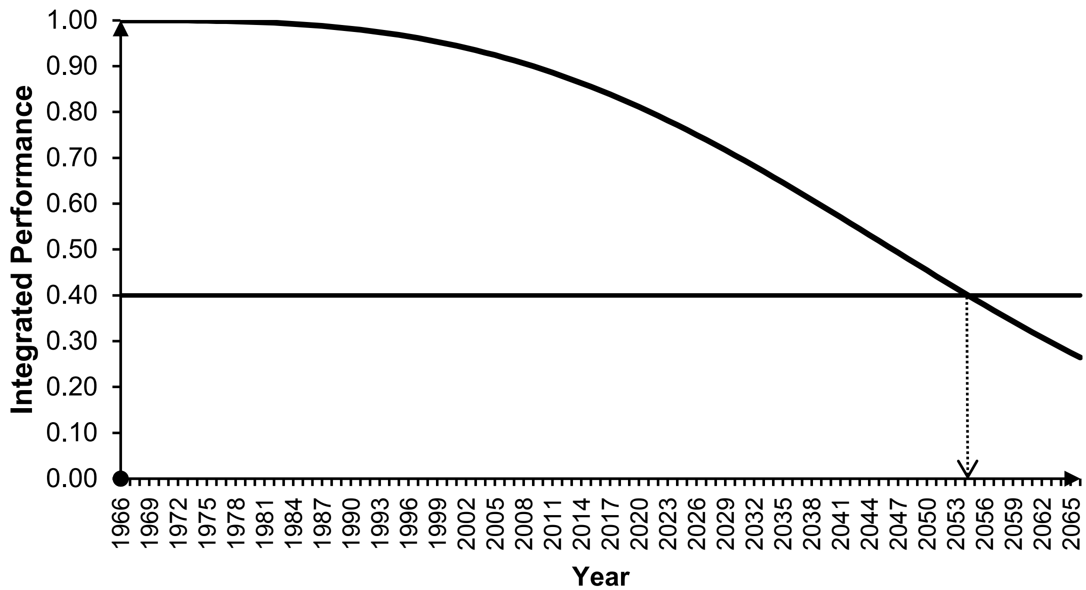


Figure 5.5 Dome (D) Component of TUN1 Performance Curve

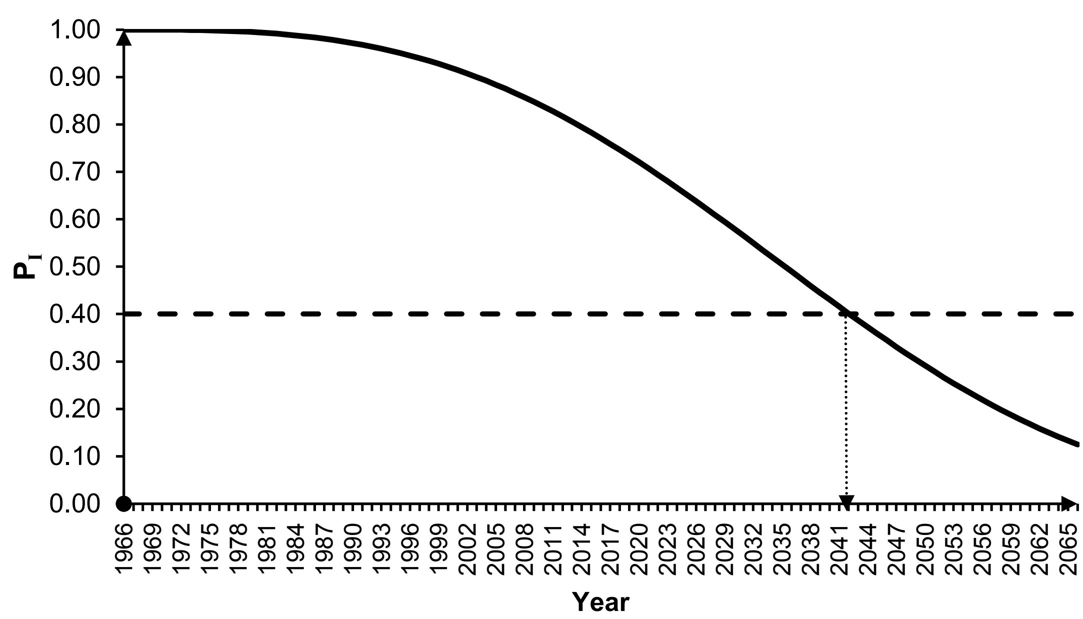


Figure 5.6 Wall (W) Component of AS1 Performance Curve

The reader is referred to Appendix C for the other performance curves of different systems. It is observed that for some component curves, the IPC is the highest curve. This is due to the fact that the integrated performance index for long periods of time after construction is high. As an example, if after 39 years the integrated performance drops from 1.0 to 0.95, the slope of the curve is lower than that of the IPC. Such is the case of components WE1, WI1, WE2, and SE2 of STA1 (refer to Appendix C). For these specific components, the integrated performance curves are higher than the rest of the components, where the IPC applies. On the other hand, if the integrated performance is assessed to be very low at a particular time of inspection, the curve slope becomes steeper. As a general observation, the IPC can be lower or higher that the UPC (or PPC) depending on the decrease of performance, and the inspection year.

5.3.4 STM Sub-Network Systems Performance Modeling

Following the evaluation of the performance model for different components in each system, the system performance model is developed. The system as defined in chapter 3 consists of its components in series, parallel or a combination of both. The systems' performance curves are based on evaluating the systems' integrated performance using the series/parallel models defined in chapter 3 for every year. The following sub-sections present and analyze the different system performance curves forming the STM Sub-Network.

5.3.4.1 Stations' Performance Modeling

The generic station performance model is shown in Figure 3.20 and evaluated using Equation 3.26. The STM sub-network consists of six stations: STA1 to STA6. STA1 to STA3 fall on the Orange line, STA4 and STA5 fall on the Green line, and STA6 is on the Yellow line. For each of these stations, an integrated performance curve is constructed.

STA1, STA2, STA4 to STA6 performance curves are illustrated in Appendix D. The performance curves for STA3 are illustrated in this section. It should be noted that all of these stations were renovated in year 2005. Hence, referring to the assumption stated in the beginning of this case study, the P_I in year 2006 jumps to a value of 0.9, and an Ideal Performance Curve continues starting from year 2006 for 90 years. The STM M&R action for STA1 is unjustified, since the P_I in 2005 was 0.6. Thus, the STM could have waited a few years to allow an integrated performance to get to the threshold value of 0.4; but this never happened. The STA2 inspection report is lost at STM; the station was renovated in 2005. The STM renovation of STA2 is also not justified, since the M&R action was done when the P_I was 0.6 (higher than the threshold). STA4 consists of four floors, thus it includes many components. Comparing performance of STA4 to the rest of the stations, it can be concluded as the number of components within a station increases, the lower the station system performance curve.

STA3 was inspected in 1997 and 2005. Thus, two performance curves have been constructed. The first is the Updated Performance Curve for the 1997 inspection; the second, is the Predicted Performance Curve of the 2005 inspection (and renovation), illustrated in Figures 5.7 and 5.8 respectively.

It can be observed from the figures that the difference between the UPC of the 1997 inspection and the PPC of the 2005 inspection before M&R is minimal. Furthermore, the M&R action improves the performance greatly.

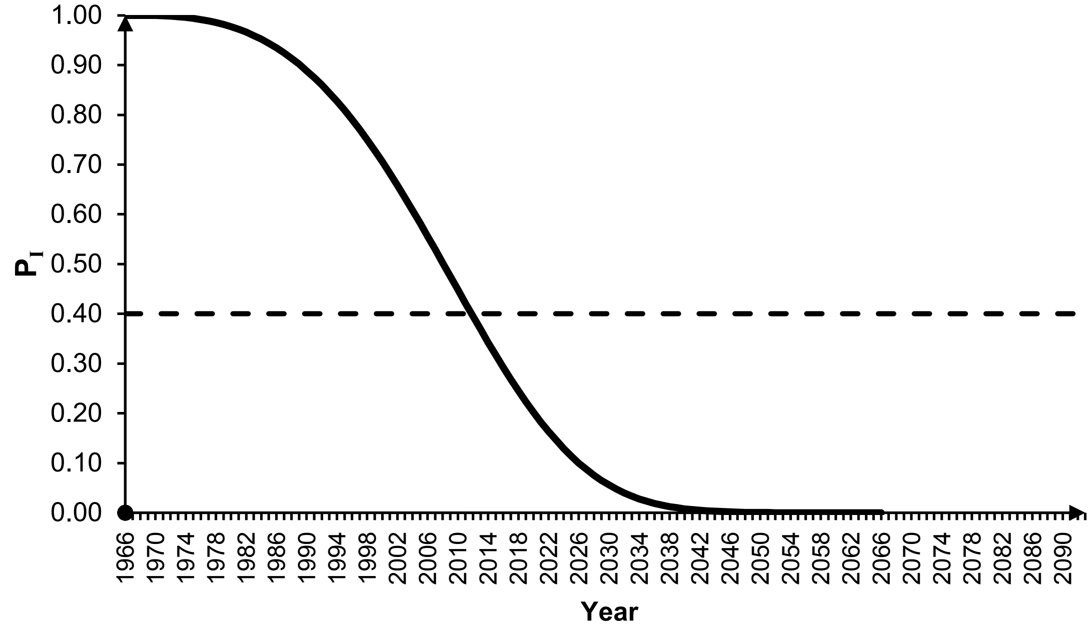


Figure 5.7 STA3 Updated Performance Curve

Figure 5.8 STA3 Predicted Performance Curve

Before M&R, the Useful Service Life (USL) - i.e. when the performance equals the threshold –is year 2015. However, after the M&R, the USL becomes year 2075. The improvement in USL is 60 years. The steady state, deterioration rate, Useful Service Life (USL) and Service Life (SL) for different stations are evaluated from the performance models and shown in Table 5.15.

Table 5.15 Stations STA1 to STA6 Performance Curves Results

Systems	**Steady State** *[No. of years]*	**Deterioration Rate** *[P_I / year]*	**USL** *[Year]*	**SL** *[Year]*
STA 1	8	0.02	2076	2093
STA 2	14	0.01	2076	2093
STA 3	8	0.02	2076	2093
STA 4	7	0.03	2076	2093
STA 5	7	0.03	2076	2093
STA 6	7	0.03	2076	2093

The steady states differ from one station to another although some similarities exist. Most of the stations have steady states between 7 and 8 years, which is very close. This means that the stations design and construction are up to the same standard. In addition, it can be stated that the external enviromental factors affecting the deterioration are uniform, (i.e. they have almost the same effect on the systems). It is only STA2 that is different. STA2 is in fact similar but does not have an inspection report. Thus, the components are assumed to follow the IPC. The station performance curve is observed higher than the rest of the stations. For this reason the steady state is 14 years instead of 7 (or 8). The deterioration rates for all stations vary between 0.01 (or 1%) and 0.03 (or 3%). Both the USL and SL are the same for all six stations, since all of them were renovated in 2005. Furthermore, they follow an IPC from 2006 on, starting with a maximum P_I of 0.9.

5.3.4.2 Tunnels' Performance Modeling

The generic tunnel performance model is shown in Figure 3.21 (refer to chapter 3. The STM Sub-Network consists of six tunnels: TUN1 to TUN6. TUN1 to TUN3 fall on the Orange line, TUN4 and TUN5 fall on the Green line, and TUN6 is on the Yellow line. For each of these tunnels, the integrated performance curves are constructed using the model defined in Equation 3.27. The tunnels performance curves are found in Appendix D. A sample (TUN1) is shown in this section. TUN1 is constructed in 1966, and inspected in 2004. The TUN1 performance curve is constructed using the series system model, and illustrated in Figure 5.9.

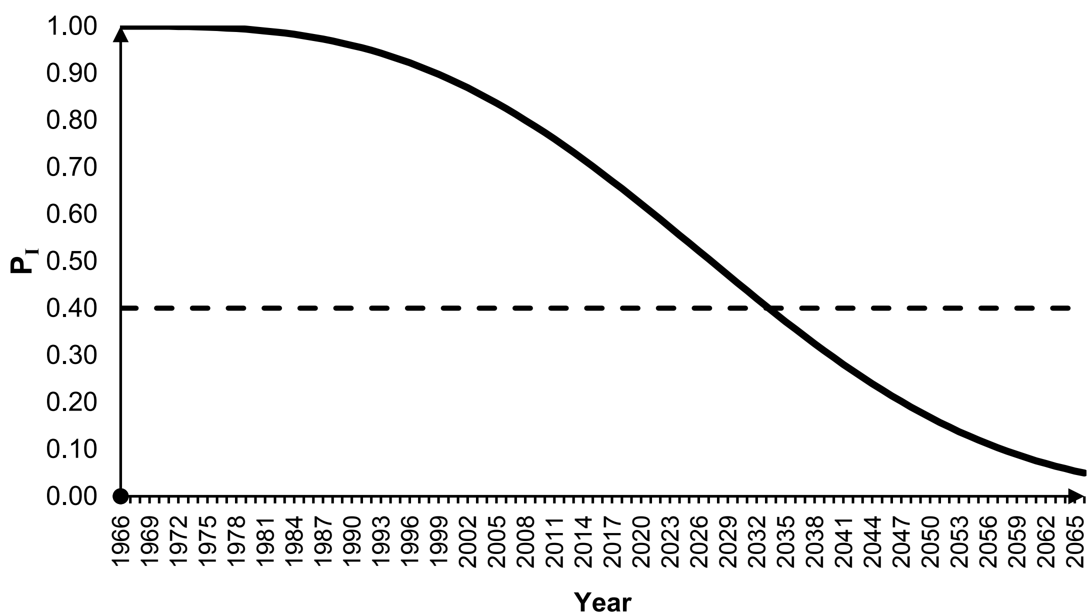


Figure 5.9 TUN1 Integrated Performance Curve

Looking at the tunnels performance curves, it can be seen that the tunnel system performance is always lower than that of its components. This observation is true since the tunnel performance is modeled as a system in series. TUN6 shows a small nuance than the rest of the tunnels. TUN6 components are not inspected; hence the integrated performance index is evaluated as 1.0. Therefore, the components performance curves follow the IPC. The TUN6 and its components performance curves match at the steady state, but the more the P_I drops, the larger the gap. The different tunnels steady state number of years, the deterioration rates, the Useful Service Life (USL) and the Service Life (SL) are tabulated in Table 5.16.

Table 5.16 Tunnels TUN1 to TUN6 Performance Curves Results

Systems	**Steady State** *[No. of years]*	**Deterioration Rate** *[P_I / year]*	**USL** *[Year]*	**SL** *[Year]*
TUN1	11	0.01	2033	2047
TUN 2	11	0.02	2029	2042
TUN 3	11	0.02	2029	2042
TUN 4	11	0.02	2030	2043
TUN 5	11	0.02	2031	2044
TUN 6	10	0.02	2023	2035

It is observed that the steady state value for the tunnels is 11 years (a slight exception is TUN6). The deterioration rate is almost the same as well, equal to 0.02. The USLs vary between 2029 and 2033 (except for TUN6), i.e. a difference of 4 years. Four years is a small difference compared to 100 years. The SLs vary between 2043 and 2047 (4 years difference). The only exception is TUN6.

As a matter of fact, TUN6 USL and SL are less than the rest of the tunnels since this tunnel is not inspected. The USL and SL difference between TUN6 and the rest of the tunnels is a minimum of 6 and 7 years respectively.

5.3.4.3 Auxiliary Structures' Performance Modeling

The generic auxiliary structure performance model is shown in Figure 3.23 (refer to chapter 3). The STM Sub-Network consists of six auxiliary structures: AS1 to AS6. AS1 to AS3 fall on the orange line, AS4 and AS5 fall on the Green line, and AS6 is on the Yellow line. For each of these auxiliary structures, the integrated performance curve is constructed using the series-parallel model defined in Equation 3.28. The auxiliary structure performance curves are found in Appendix D. As a general observation, the auxiliary structures are not often inspected as the stations and the tunnels. In the STM Sub-Network, the AS1 and AS4 are the only inspected auxiliary structures.

The AS4 performance curve is shown in Figure 5.10 as a sample. AS4 is inspected in 1995, (i.e. after 29 years). Since the AS4 wall component has shown some deterioration, while the bottom and top slab components show minor deterioration, the wall performance curve is very close to the AS4 performance. The wall component is in series with the parallel sub-system of the top and bottom slab. Comparing the auxiliary structure performance curve to that of its components, it is observed that the auxiliary structure performance curve is lower than that of the components. This is due to the nature of the AS series-parallel model. However, the difference between the auxiliary structure performance curve and its components performance curves is less than the difference between the curves for the tunnels and stations. The steady state number of years, the deterioration rate, the Useful Service Life (USL) and Service Life (SL) of the auxiliary structures AS1 to AS6 are tabulated in Table 5.17.

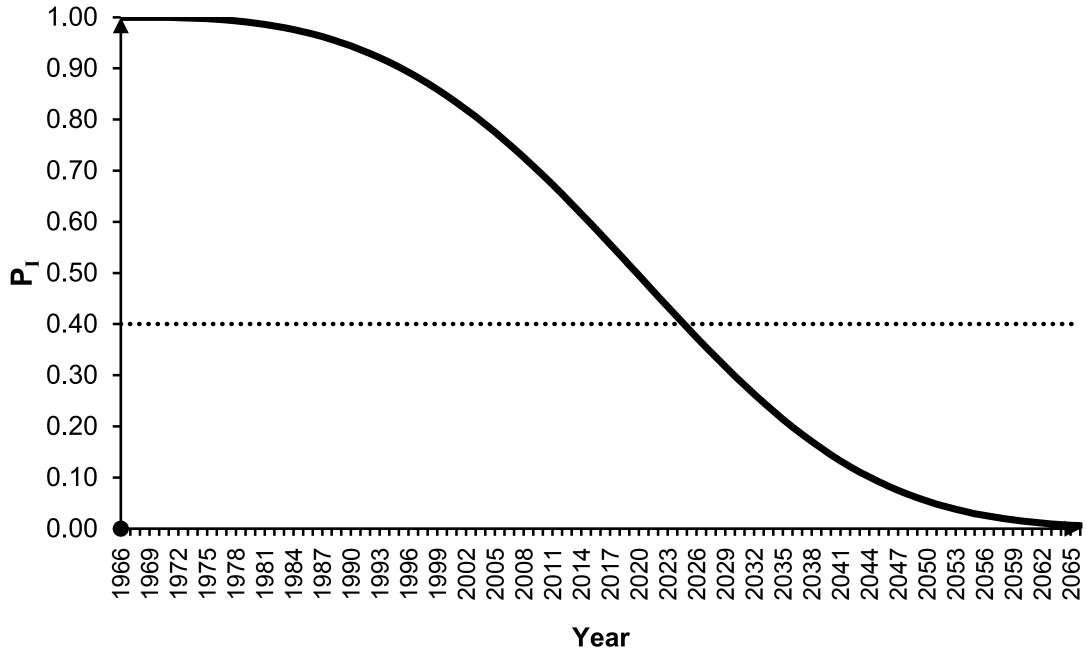


Figure 5.10 AS4 Integrated Performance Curve

Table 5.17 Auxiliary Structures AS1 to AS6 Performance Curves Results

Systems	**Steady State** *[No. of years]*	**Deterioration Rate** *[P_I / year]*	**USL** *[Year]*	**SL** *[Year]*
AS 1	13	0.02	2036	2048
AS 2	14	0.02	2040	2053
AS 3	14	0.02	2040	2053
AS 4	10	0.02	2024	2036
AS 5	14	0.02	2040	2053
AS 6	14	0.02	2040	2053

The non-inspected auxiliary structures have a steady state of 14 years. AS1, which is slightly deteriorated, has a steady state of 13 years. It is only AS4 that showed some deterioration in 1995, and has a steady state of 10 years. Similarly, the non-inspected auxiliary structures have a USL and SL of 2040 and 2053 respectively. While AS1, which is slightly deteriorated has a USL equal to 2036, and an SL equal to 2048. It is only AS4 that showed some deterioration in 1995, has a USL equal to 2024 and an SL equals to 2036.

5.3.5 STM Sub-Network Lines Performance Modeling

The next step in the SUPER model is to evaluate line performance. The lines consist of the different systems physically on the lines. The STM Sub-Network consists of three lines: Orange, Green and Yellow. The Orange line consists of 9 systems (3 stations, 3 tunnels, and 3 auxiliary structures). The Green line consists of 6 systems (2 stations, 2 tunnels and 2 auxiliary structures). While, the Yellow line consists of 3 systems (1 station, 1 tunnel and 1 auxiliary structure). Refer to Figure 3.24 for the evaluation of a generic line performance model.

The Orange line comprises STA1 to STA3, TUN1 to TUN3 and AS1 to AS3. Each system performance curve was evaluated in the previous section. The Orange line performance model was evaluated using Equation 3.29, and its performance curve is shown in Figure 5.11. Comparing the Orange line performance curve with its systems, it is observed that the Orange line performance curve is higher than that of its systems. In addition, the improvements (M&R actions) of the stations are echoed in the line performance curve, to a lesser degree. It can be stated that the performance of the Orange line is better than the performance of its systems independetly.

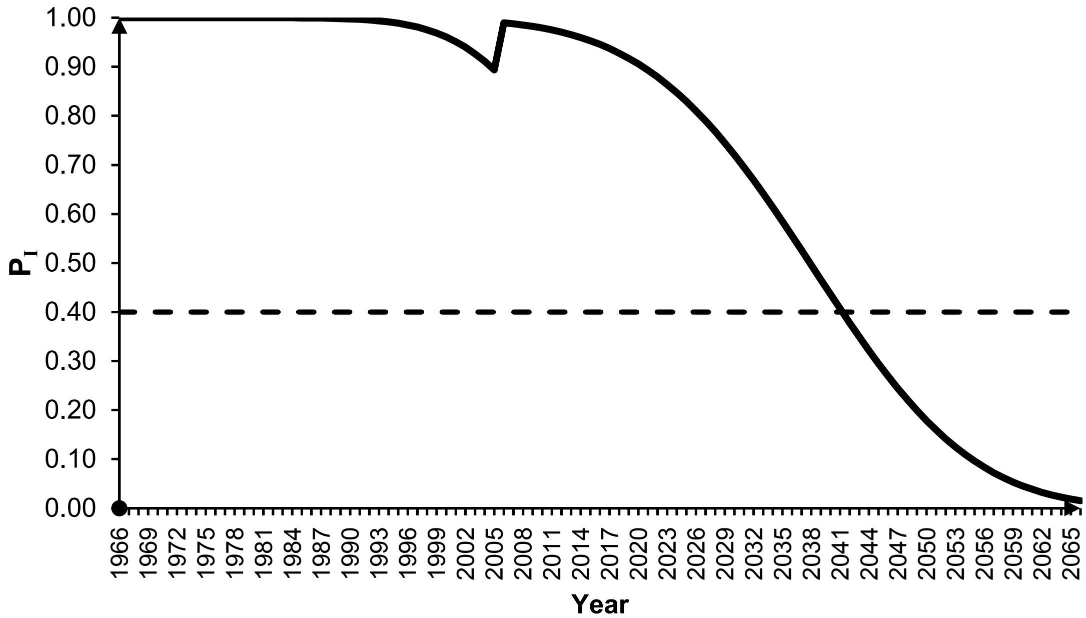


Figure 5.11 Orange Line Integrated Performance Curve

The Green line comprises STA4, STA5, TUN4, TUN5, AS4, and AS5. The Green line contains less systems than the Orange line. The line performance model is defined in Equation 3.29 and illustrated in Figure 5.12. The Green line performance curve is oberserved to be closer to the curves of its systems. Even the stations M&R improvement in the performance is considerabely echoed in the Green line performance curve. These two observations are due to the fact that the Green line has a number of systems less than the Orange line.

The Yellow line comprises only STA6, TUN6 and AS6. The line performance model is defined in Equation 3.29 and illustrated in Figure 5.13. The Yellow line performance curve is lower than that of its systems. Thus, it can be stated that the fewer the number of systems in a line, the lower the line performance curve compared to its systems performance curves. So the line performance curve is directly related to the number of the systems in that line. The Orange, Green and Yellow lines performance steady states, deterioration level, USL and SL are shown in Table 5.18.

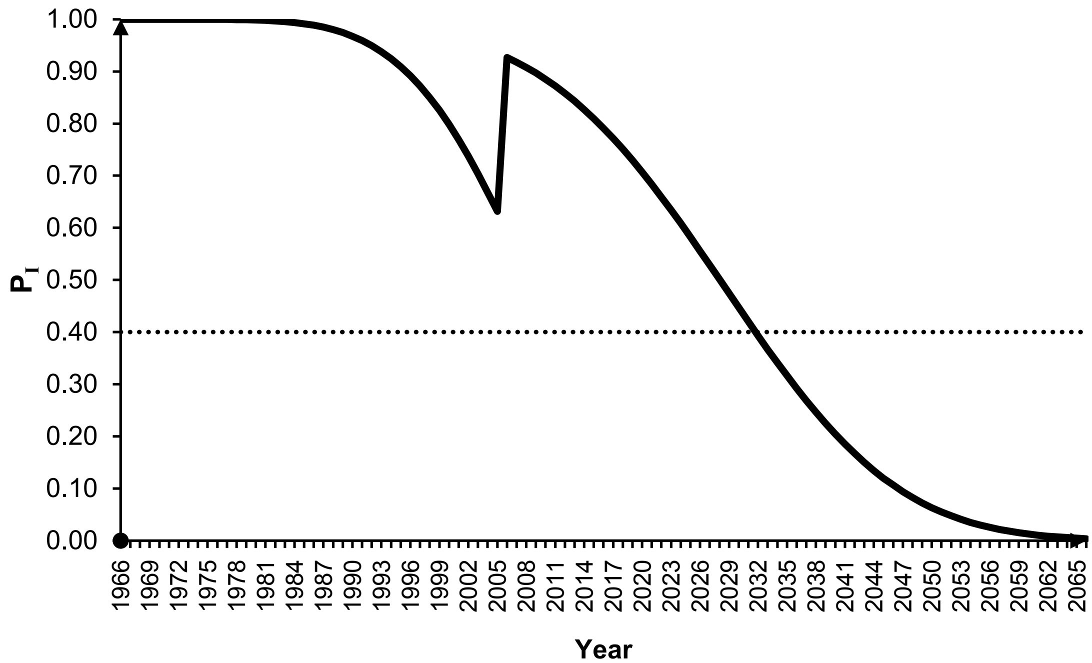


Figure 5.12 Green Line Integrated Performance Curve

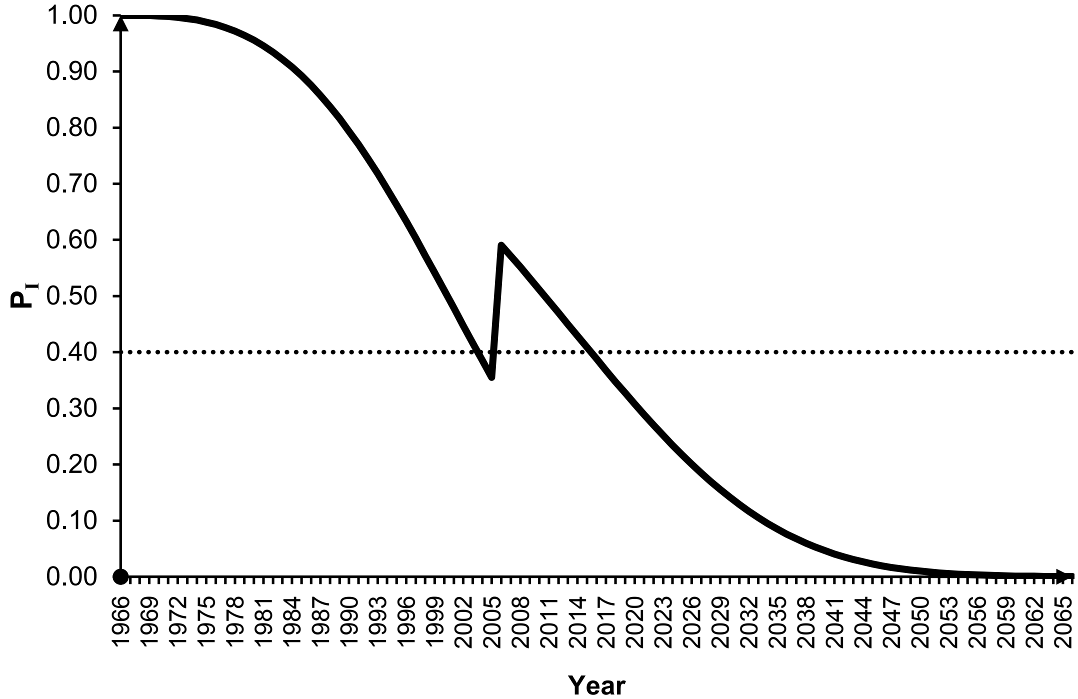


Figure 5.13 Yellow Line Integrated Performance Curve

Table 5.18 Lines Performance Curves Results

Line	**Steady State** *[No. of years]*	**Deterioration Rate** *[P_I / year]*	**USL** *[Year]*	**SL** *[Year]*
Orange	26	0.02	2041	2049
Green	17	0.02	2032	2040
Yellow	6	0.02	2015	2026

It can be stated that the higher the number of systems in one line, the higher the number of years in the steady state. Thus, the Orange line has the highest steady state number, equal to 26 years, whereas the Green line has 17 years, and the Yellow line has only 6 years. The deterioration rate is almost the same for the three lines. Consequently, the USL and SL differ due to the steady state difference between the lines.

5.3.6 STM Sub-Network Performance Modeling

The final step in the SUPER model is the evaluation of the complete network performance curve. The STM Sub-Network performance curve is evaluated from the three lines in parallel. Refer to Figure 3.25 for the evaluation of the network performance model.

The STM Sub-Network integrated performance model is defined in Equation 3.30 and the performance curve illustrated in Figure 5.14. Comparing the Sub-Network performance curve to its lines, it is observed that the Sub-Network performance curve is higher than that of its lines. This is true since the performance is modeled as a parallel system one. Hence, It can be stated that even if individual systems (stations, tunnels and auxiliary structures) decrease in performance, the whole network still performs adequately.

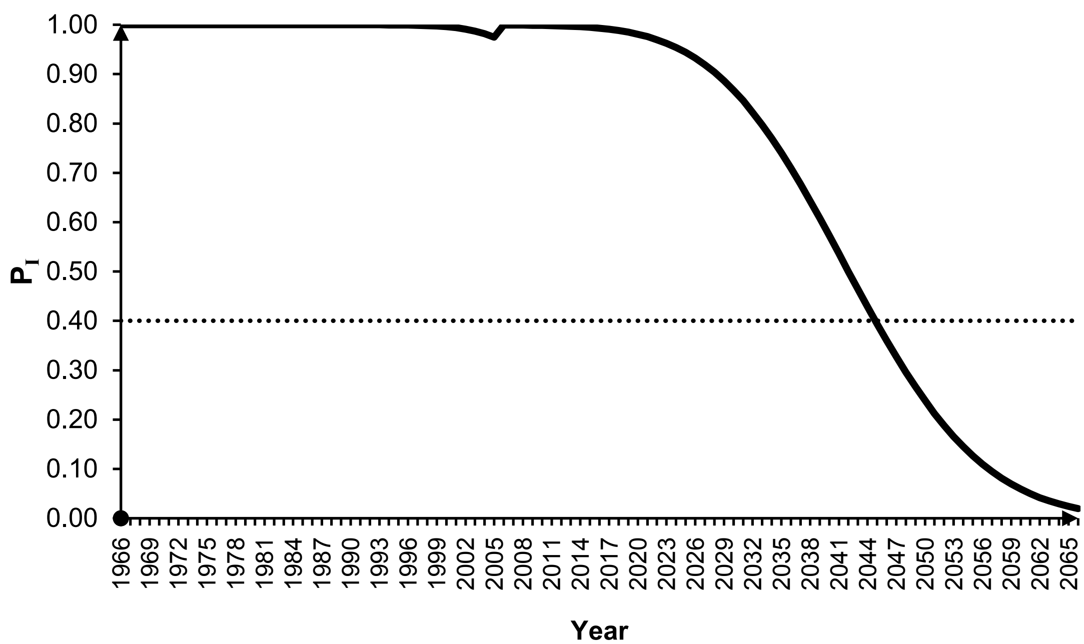


Figure 5.14 STM Sub-Network Integrated Performance Curve

The results derived from the Sub-Network performance model and curve are tabulated in Table 5.19. The STM Sub-Network deterioration rate is the highest between all systems and lines. However, the steady state time is long (35 years), and the USL is at 2045. This means that STM can at the most wait until the year 2045 in order to plan a full and complete M&R of the entire network.

Table 5.19 STM Sub-Network Performance Curves Results

Network	**Steady State** *[No. of years]*	**Deterioration Rate** *[P_I / year]*	**USL** *[Year]*	**SL** *[Year]*
STM Sub-Network	34	0.035	2045	2052

5.3.7 Performance Analysis for a Case Study

The STM Sub-Network is checked for the current year (2011) and after 10 years (2021). For each year, the integrated performance index is recorded using the model and the performance curves developed in the previous sections. Table 5.20 shows the integrated performance index for 2011and 2021. It also shows the difference in percentage between the two indices and the deterioration rate during this ten-year period.

Table 5.20 STM Case Study Results

System / Line / Network	P_I 2011	P_I 2021	ΔP_I (%)	Deterioration Rate
STA1	0.9	0.89	1%	0.10%
STA2	0.9	0.89	1%	0.10%
STA3	0.9	0.89	1%	0.10%
TUN1	0.76	0.61	20%	1.50%
TUN2	0.72	0.54	25%	1.80%
TUN3	0.71	0.54	24%	1.70%
AS1	0.81	0.67	17%	1.40%
AS2	0.85	0.72	15%	1.30%
AS3	0.85	0.72	15%	1.30%
Orange Line	0.98	0.89	9%	0.90%
STA4	0.9	0.89	1%	0.10%
STA5	0.9	0.89	1%	0.10%
TUN4	0.73	0.56	23%	1.70%
TUN5	0.74	0.57	23%	1.70%
AS4	0.67	0.47	30%	2.00%
AS5	0.85	0.72	15%	1.30%
Green Line	0.87	0.68	22%	1.90%
STA6	0.9	0.89	1%	0.10%
TUN6	0.64	0.45	30%	1.90%
AS6	0.85	0.72	15%	1.30%
Yellow Line	0.49	0.29	41%	2.00%
STM Sub-Network	1.00	0.98	2%	0.20%

The stations show little difference between 2011 and 2021 since they were renovated in 2005. The rate of deterioration is small (0.1%). However the tunnels lose between 20% and 24% of the performance in ten years, and the rate of deterioration varies between 1.5% and 1.9%. This means that the tunnels lose aapproximately 22% of their assets in 10 years, which represents a significant loss. Moreover, after 2021, the STM must think of an M&R action since the average performance index will reach a value of 0.54, near the threshold (0.4). TUN6 is more alarming, since in 2021 the performance index is closer to the threshold (0.45), thereby requiring an M&R action before or in 2021.The auxiliary structures show a performance difference of 15% on the average, except for AS4 where the difference is 30%. Thus, the STM must consider an M&R action before 2021, especially that the performance index in 2021 (0.47) is close to the threshold (0.40).

The Orange line shows little deterioration in the coming ten years. Although not alarming, the Green line, on the other hand shows a loss of 20% of performance, which is high. The performance index reaches a value of 0.68 in 2021. If preventive actions are planned before 2021, especially for AS4 and the tunnels, the Green line performance index will improve. The main problem facing the STM for the next ten years (if looking at the Sub-Network solely) is the Yellow line. Considerable deterioration in the few system that comprise the Yellow line lead to an important deterioration of the Yellow line as a whole, with a deterioration rate of 2.0%, and an index difference of 40%. Furthermore, the performance index in the year 2021 shows a level significantly below the threshold (0.29), though higher than the critical level. Although the STM faces a problem in the Yellow line, the whole Sub-Network still functions properly. The deterioration rate is low, and the difference between the indices is small. Regardless of the deteriorating integrated condition of the Yellow line, the Sub-Network is not affected to a significant extent. The main cause is that the Yellow line consists of three systems, out of 18 systems in the whole Sub-Network. The M&R actions done in 2005 on the stations affect significantly the Sub-Network performance.

This case study emphasizes the flexible and beneficial usage of the performance curves developed using the SUPER model.

5.4 SENSITIVITY AND ADDITIONAL ANALYSES

5.4.1 Analysis of the 'Year of Construction' Effect

The STM Sub-Network systems analyzed in this research had the same year of construction. However this is not the case for all the systems in the entire STM network. The construction years of the STM systems range from 1966 to 2006, while the inspection years are almost the same for all systems (1992, 1997, 2004 and 2005). Hence, it is very important to analyze the different integrated performance curves of systems with different construction years. Inspection reports for systems constructed in 1966, 1976, 1978 and 1982 are available but reports for systems constructed in 1987, 1988, 2003 and 2006 are missing.

One station at each year of construction is selected since the stations are the most complex systems in a network. The following stations are analyzed: Henri Bourrassa (STA7), Pie IX (STA8), Verdun (STA9), and Côte Ste Catherine (STA10), which were constructed in 1966, 1976, 1978 and 1982, respectively. The important information for these stations, such as station name, the construction year, the inspection years and the M&R action years are tabulated in Table 5.21.

Table 5.21 Selected STM Stations Information Table

Station No.	Line	Station Name	Station No.	Construction Year	Inspection Years	M&R Year
1	Orange	Henri Bourassa	STA 7	1966	2005	2005
2	Green	Pie IX	STA 8	1976	2004	2008
3	Green	Verdun	STA 9	1978	2004, 1996	2008
4	Orange	Côte Ste Catherine	STA 10	1982	1996	2010

It is observed that for some stations the inspection and construction years are close. For example, STA10 station was inspected in 1996, while constructed in 1982 (14 years difference) and repaired in 2010 (28 years after construction). It seems that many structural problems are encountered in this particular station. Problems could be due to several reasons such as design errors, construction errors, water infiltration problems and construction of nearby buildings not considered in the design. It should be noted also that these stations (except STA7) were renovated, although they were not part of any renovation program. The STM confirmed that the renovation of these stations depended on the results from inspection reports. The integrated performance curves are constructed using the SUPER model independently as illustrated in Figure 5.15. This figure shows the performance curves of STA7 to STA10 on one graph. The purpose of this figure is to observe the change of the performance curves for different construction years.

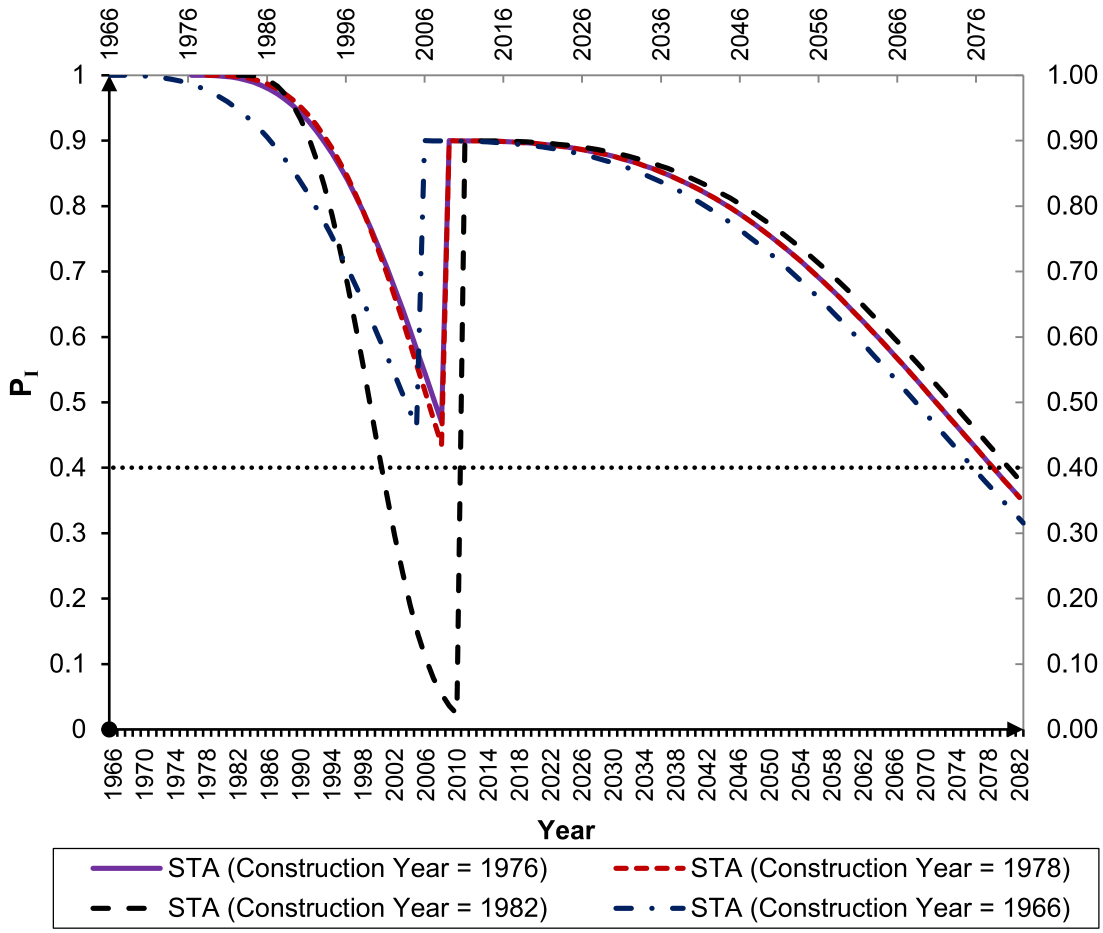


Figure 5.15 STA7 TO STA10 Integrated Performance Curves

Analyzing Figure 5.15, it can be stated that the smaller the difference between the construction and inspection year, the steeper the slope of the performance curve, or simply the higher the deterioration rate (before M&R of course). Thus, it can be observed that the highest deterioration rate (curve slope) is for the station constructed in 1982, while the smallest deterioration rate (curve slope) is for the 1966 station. The deterioration rates are 3.0%, 3.5%, 4.0% and 4.5% for the stations constructed in 1966, 1976, 1978 and 1982, respectively. This fact is true, because the inspection show significant deterioration after a short period from construction, thus, the rate of deterioration is high while the steady state is low.

The steady states are 7, 6, 5 and 3 years for station constructed in 1966, 1976, 1978 and 1982, respectively. This is further confirmed in real life. In fact, the 'Côte Ste Catherine' (STA10) station was closed in 2010 due to major repair works.

5.4.2 Sensitivity Analysis of the Cracks and Defects Weights

The SUPER model application to the STM Sub-Network used the cracks and defects weights evaluated using AHP data from the questionnaires. The AHP method is a subjective method; however, it account for some inconsistency. Referring to the statistical analysis in the first section of this chapter, it is shown that the structural cracks and defects' weights vary in a range between -40% and +40% for a 95% confidence level. Hence, it is necessary to analyze the sensitivity of the integrated performance curves to the change of cracks and defects' weights. However, since the resulting output of the model is a not a single answer, rather a curve for 100 years (a P_I for each year), thus 100 answers, it is not possible to analyze the sensitivity using well-known software (such as @Risk, or CrystallBall) or Excel add-ons. Therefore, the sensitivity analysis is done in three steps:

1. The most important cracks and defects are selected. The major structural cracks are the '*shear crack*' (SHC), and '*continued movement*' (CM). Whereas, the major structural defects are '*rebar corrosion*' (RCOR), and '*efflorescence*' (EFFL). In addition, the secondary '*crack*' (C) is also selected, since it is the most encountered defect in the structural components.

2. Change the weights of the chosen cracks and defects from -40% to +40% (-40%, -30%, -20%, -10%, +10%, +20%, +30%, +40%) of the original weight.
3. Run the SUPER model on the STM Sub-Network.
4. Analyze the change of the performance curves in systems, lines and the Sub-Network.

The selected systems for this particular sensitivity analysis are: 1) STA4 since it consists of four floors and is inspected in 1992, 1997 and 2005; 2) AS4 since it is the only inspected auxiliary structure; and 3) TUN4 adjacent to STA4 and AS4, inspected in 2004. First, the STA4, TUN4 and AS4 performance curves under the cracks and defects weights change are constructed. The rest of the systems performance curves are then constructed. The performance curves for the Orange, Green and Yellow lines are constructed. Finally, the STM Sub-Network performance curve is constructed. However, only the STA4, TUN4, AS4, Green line, and STM Sub-Network performance curves are shown hereafter.

The STA4 integrated performance curves for the original cracks/defects weights, and the different cracks/defects weights change from -40% to +40% of the original weights are constructed and plotted in Figure 5.16. It can be observed that the change in the cracks and defects weight changes the performance curve. It is noted that the performance curve becomes lower due to the increase of the weights change (+40%). On the other hand, the performance curve becomes higher due to the decrease of the weights change (-40%). The highest difference is at year 2005 (i.e., directly before the renovation). When the cracks and defects' weights change to -40% of the original weight values, the performance in 2005 becomes 0.47 (higher than the original one, which is 0.39). However, when the cracks and defects weights change to +40% of the original weight values, the performance becomes 0.32 (thus lower than the original value). Hence, the change in the performance index in 2005 is approximately ±20%. The steady state is relatively the same due the cracks and defects change in weights. The only missing information in the above figure is the service life change. In order to analyze the change of the Useful Service Life of STA4 due to the change of the cracks and defects weights, the STA4 performance without the M&R action should be constructed (using the 2005 inspection).

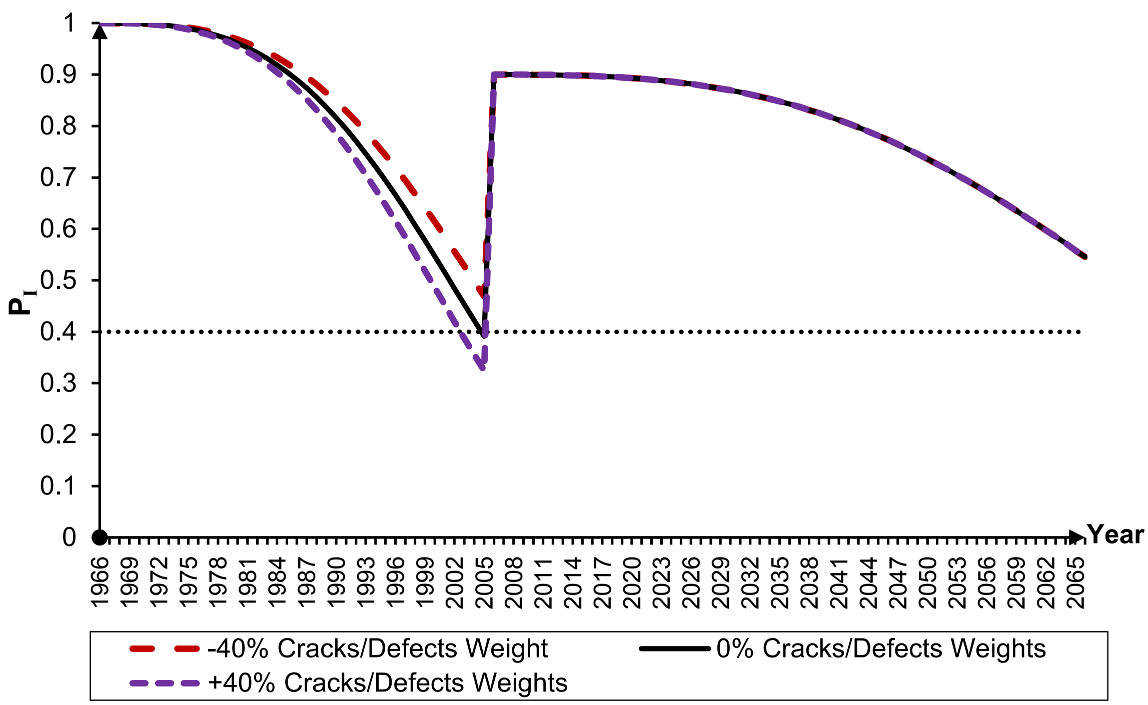


Figure 5.16 STA4 Performance Curves for Cracks/Defects Weights Change

STA4 integrated performance curves without the M&R for the original cracks/defects weights, and the different cracks/defects weights change from -40% to +40% the original weights are constructed and plotted in Figure 5.17. The station integrated performances curve after the inspection of year 2005 are analyzed, however without the M&R action of that same year.

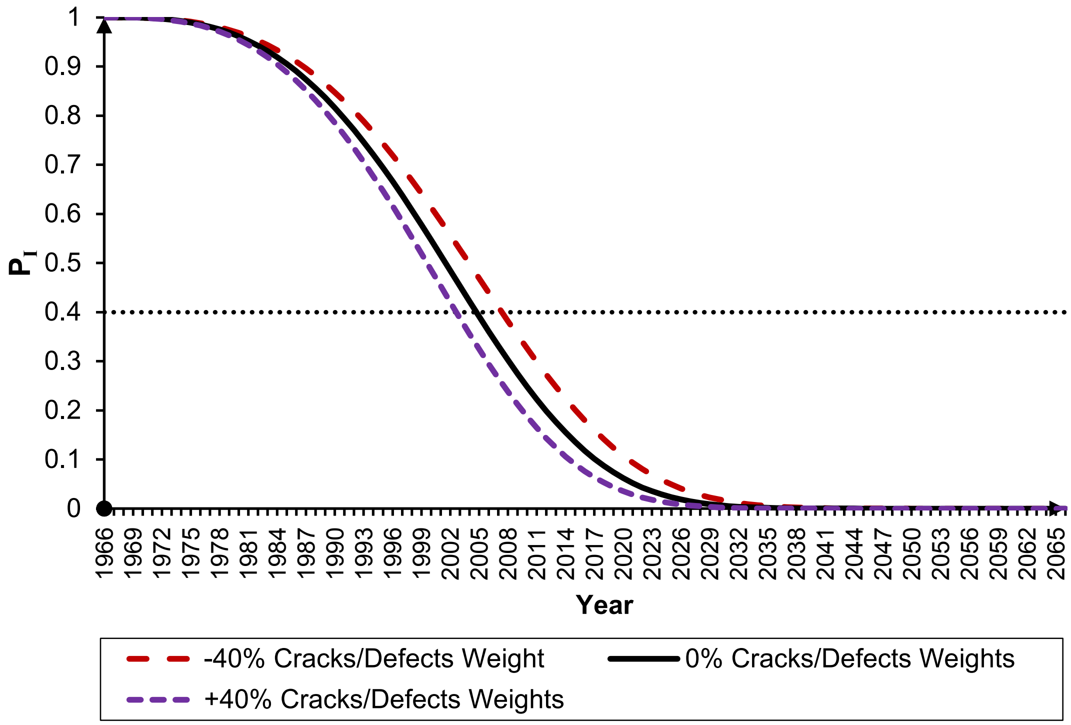


Figure 5.17 STA4 Performance Curves (No M&R) for Cracks/Defects Weights Change

It is noted that the performance curve becomes lower due to the increase of weights (+40%). In contrast, the performance curve becomes higher due to the decrease of the weights (-40%). The difference between the extreme weight changes (+40% to -40%) at the performance threshold level is only 4 years (between 2003 and 2007; i.e. a 5% change). However, the difference at the service life (when the performance index is equal to 0.2) is 6 years or ±3 years. If the original Service Life of STA4 is 46 years (2012-1966), the difference in Service Life due the cracks and defects wieghts change is 3/46 = 6.5% only.

Thus, it can be concluded that due to cracks and defects weights change, the station steady state remains the same, the change of performance is arround 20%, and the change of both the Useful Service Life and the Service Life is 5% and 6.5% respectively.

TUN4 integrated performance curves for the original cracks/defects weights, and the different cracks/defects weights change from -40% to +40% the original weights are constructed and plotted in Figure 5.18. The TUN4 integrated performance curves after the inspection of year 2004 are analyzed.

It is also noted that the performance curve becomes lower due to the increase of the weights change (+40%). On the other hand, the performance curve becomes higher due to the decrease of the weights change (-40%). The difference between the extreme weight changes at the performance threshold level is only 8 years (between 2034 and 2026), i.e. ±4 years. The original USL is 64 years, thus the USL change 6%. The original Service Life (when the performance index is equal to 0.2) of this particular station is equal to 77 years (SL=2043-1966=46). The difference in SL is noted as ± 5 years. Thus, 5 years out of 77 years is 6%.

In addition, TUN4 shows a change of performance index at the performance threshold year equal to 17%. Thus, it can be concluded that due to the chamge in the cracks and defects weights, the tunnel steady state remains the same, the change of performance is 17%, and the change of both the useful service life and service life is 6%.

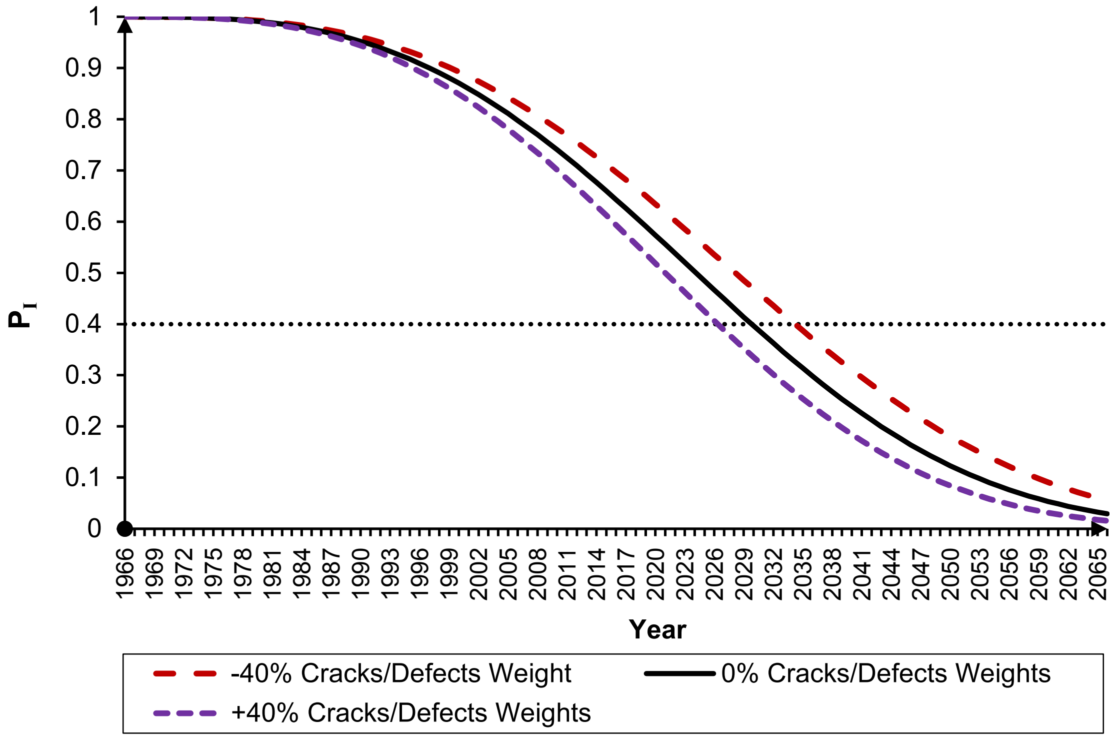


Figure 5.18 TUN4 Performance Curves for Cracks/Defects Weights Change

AS4 integrated performance curves for the original cracks/defects weights, and the different cracks/defects weights change from -40% to +40% the original weights are constructed and plotted in Figure 5.19. The AS4 auxiliary structure integrated performance curves after the inspection of year 1995 are analyzed.

It is also noted that the performance curve becomes lower due to the increase of the weights change (+40%). In contrast, the performance curve becomes higher due to the decrease of the weights change (-40%). It is observed that the difference between the extreme weight changes at the performance threshold level is only 6 years (between 2022 and 2028), i.e. ±3 years. Hence, the difference in the Useful Service Life is 5%. The difference in the performance index when the original curve touches the threshold is 16%. The service life of this particular station is equal to 70 years for the original cracks and defects weights (SL = 2036-1966 = 70). It is observed that the difference in the Service Life is ± 4 years. Thus, 4 years out of 70 years is 5.7%. Thus, it can be concluded that due to cracks and defects weights change, the auxiliary structure steady state remains the same, the change of performance is arround 16%, and the change of both the Useful Service Life and the Service Life is arround 5%. The same procedure and analysis is repeated for all systems. The results are deemed similar.

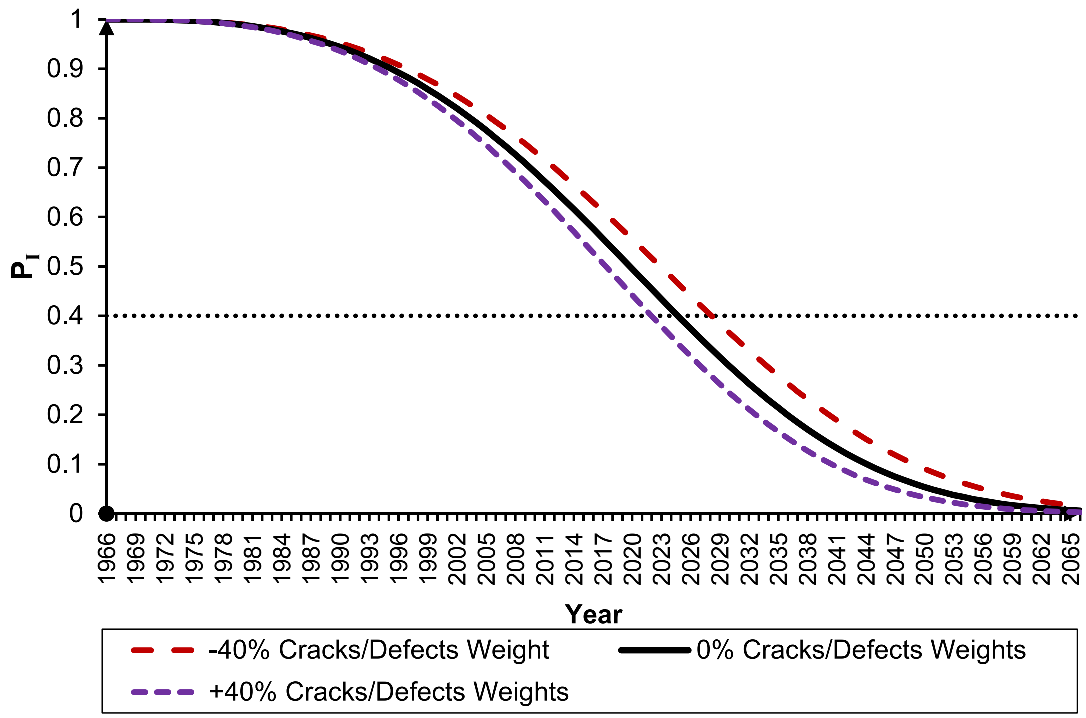


Figure 5.19 AS4 Performance Curves for Cracks/Defects Weights Change

The Green line integrated performance curves for the original cracks/defects' weights, and the different cracks/defects weights change from -40% to +40% the original weights are constructed and plotted in Figure 5.20. Similar to the systems, the performance curve becomes lower due to the increase of the weights change (+40%). The performance curve becomes higher due to the decrease of the weights change (-40%). If the cracks and defects weights change down to -40% or up to +40%, the performance index changes ±9% in 2005, and ±20% at the USL year (2032). Now the USL changes ±3 years. If the original USL is 66 years , so the change in USL is 4.5%. The SL changes ±4 years. If the original SL is 74 years, so the change in SL is 5.4%.

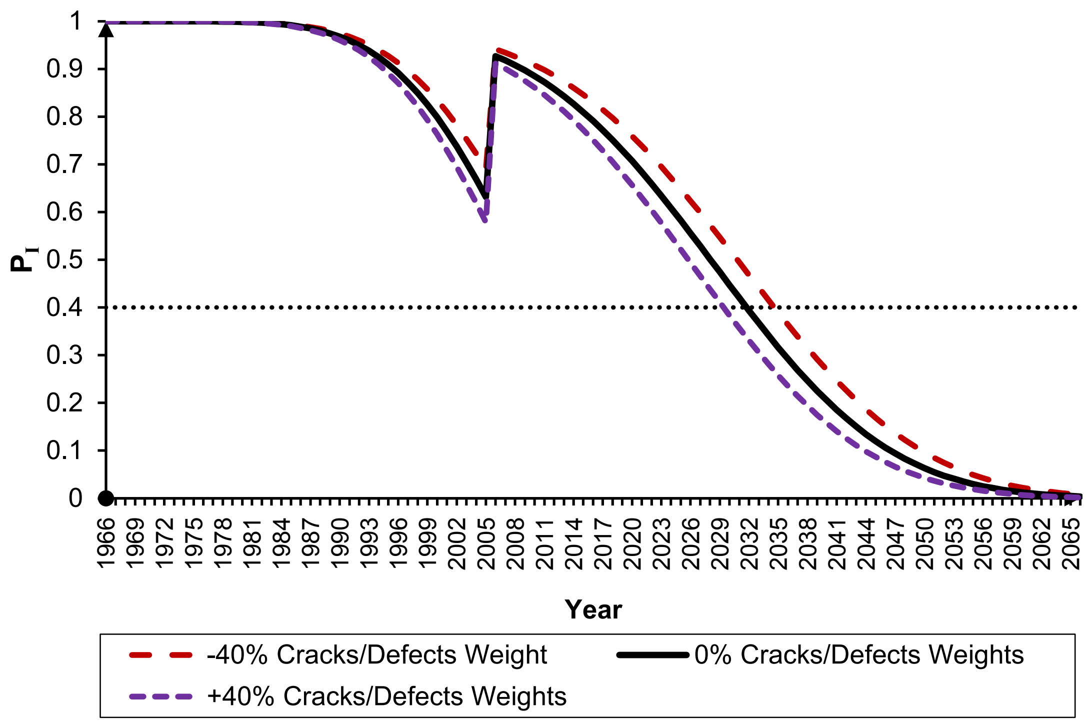


Figure 5.20 Green Line Performance Curves for Cracks/Defects Weights Change

It can be concluded, that the line performance curve remains the same due to the change in the cracks and defects weights. However, the performance changes between 9% and 20%. Moreover, both the USL and the SL changes around 5%. This analysis is repeated on the Orange and Yellow lines, and similar conclusions were observed.

The STM Sub-Network integrated performance curves for the original cracks/defects weights, and the different cracks/defects weights change from -40% to +40% the original weights are constructed and plotted in Figure 5.21. If the cracks and defects weights change down to -40% or up to +40%, the performance index does not change in 2005, however it changes ±25% at the USL year (2045). Now the USL changes ±3 years. If the original USL is 79 years, so the change in USL is 3.8%. The SL changes ±2 years. If the original SL is 86 years, so the change in SL is 2.3%.

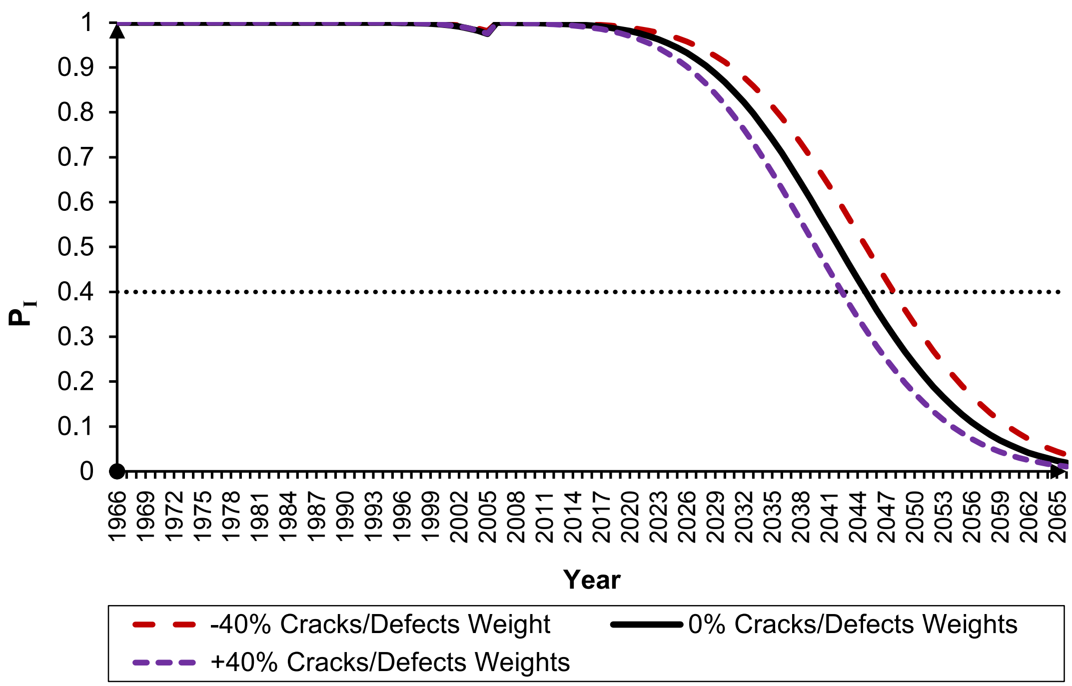


Figure 5.21 Sub-Network Performance Curves for Cracks/Defects Weights Change

As a general conclusion, it is noted that if the cracks and defects' weights change between -40% and +40% of the original weight calculated from the questionnaires: i) the performance changes between ±16% to ±25%, ii) the USL year changes around ±5%, and iii) the SL changes around ±5% as well.

5.4.3 Sensitivity Analysis of the Cracks and Defects Scores

Another sensitivity analysis is performed in order to assess the effect of the change of cracks and defects' scores on the performance curves. This additional analysis considers the change in the cracks and defects scores to be between -40% and 0% of the original scores. The @RISK software is used for this type of analysis. The selected changed inputs are the scores of STA4, TUN4, and AS4, and the monitored output is the Green line performance index in 2005, i.e. directly before the M&R action in STA4 (and STA5). Table 5.22 summarizes this sensitivity analysis, by showing the integrated performance index at 2005 for the Green line with the change (in percent) of the defects/cracks scores in the different components (WE4 in STA4, W in TUN4, and W in AS4).

It is observed that the change in the performance index is a drop from 0.63 to a minimum of 0.55. Thus the change in performance is -15% for a 40% change in cracks and defects scores. The change of scores increasing to +40% cannot be analyzed, since the scores are bounded by the unity value. It can be also noted that the change in cracks and defects scores in stations has a higher effect on the line performance than the rest of the systems (tunnels and auxiliary structures).

Table 5.22 Green Line Integrated Performance Index Change for Scores Change

	WE4 (STA4)	W (TUN4)	W (AS4)
Scores (% Change)	Mean Green Line P_I(2005)	Mean Green Line P_I(2005)	Mean Green Line P_I(2005)
-40%	0.55	0.59	0.59
-33%	0.56	0.60	0.60
-27%	0.58	0.60	0.60
-20%	0.59	0.61	0.61
-13%	0.60	0.62	0.62
-7%	0.62	0.62	0.62
0%	0.63	0.63	0.63

5.5 SUPER MODEL TESTING

Due to the scarcity of systems' inspection reports on one hand and the result of the model, being a curve (or set of curves) on the other, it is difficult to perform a regular model validation. One way to perform model testing is to compare the new model results with previous and existing models. Hence, the SUPER model performance curves may be compared to performance curves evaluated by Markov Chain and regression models (refer to literature review chapter). First, the Markov Chain (MC) model is difficult to assess since no regular inspection data is found. Thus, the MC Transition Probability Matrices (TPM) are based on assumptions. Therefore, there is no benefit of comparing the SUPER model curves to a Markov Chain assumption-based model. Second, regression performance model is difficult to obtain, since regression requires a great deal of data. The regression model is based on assumptions and not real data. Thus, comparing the SUPER model to an assumption-based regression model is useless. Therefore, two testing approaches are considered and performed in this research: i) testing the SUPER model against real situations and ii) testing the PPC of SUPER model against the IPC.

5.5.1 Testing the SUPER model against real situations

The first testing approach lies in comparing the SUPER model performance indices at the inspected and M&R actions against real situations. STA1 and STA3 were renovated in 2005, when the SUPER model shows a P_I in 2005 equal to 0.61. STA2, STA4, STA6 and STA7 are also renovated in 2005. The respective SUPER model P_I in 2005 varies between 0.35 and 0.52 (low). Hence, the M&R is justified. For these cases, the SUPER model result matches the STM decisions. The 'Côte Ste Catherine' station (STA10) was found to be extremely deteriorated before the year 2010. The SUPER model evaluates an integrated performance index (P_I) in 2010 equals to 0.02 (approximately nil). It is already been noted that this station was closed during the summer of 2010 for major repair work. Thus, the SUPER model matches the real situation for this specific station. Looking further on STA3 PPC based on the 1997 inspection, the P_I in 2005 is 0.61. On the other hand, the P_I in 2005 is 0.58, based on the PPC of the 2005 inspection. Thus, the difference is minimal and equals 5%. Now the difference of P_I for STA4, inspected in 1992, 1997 and 2005, at year 2005 is 0.32, 0.32 and 0.39 respectively. Here the difference is 20%. Thus it can be concluded the SUPER model matches real situations with a difference of maximum 20%.

5.5.2 Testing the SUPER model PPC against the IPC

Since it is difficult to perform a validation for the complete set of performance curves resulting from the SUPER model and since the number of available inspection reports is small, meaning the systems cannot be divided into training and test samples, another particular method is used in this research for testing the model. This research adopts a straightforward method, which consists of calculating a Verification Indicator (VI). The Verification Indicator (VI) is defined in Equation 5.1:

$$VI = \frac{MPI}{IPI} \tag{5.1}$$

Where MPI = Model Performance Index, and IPI = Ideal Performance Index

The Verification Indicator (VI) is evaluated at the inspection years of the systems. Thus, only the systems that have inspection years are selected. The Model Performance Index (MPI) is the respective integrated performance index at the inspection year, when the performance curve is updated, using a PPC. The Ideal Performance Index is the respective integrated performance index at the inspection year if an Ideal Performance Curve (IPC) is evaluated. The IPC is a result of the Weibull reliability function, so it is used as a reference curve of deterioration. Therefore, the main idea here is to compare and measure the difference between the predicted (updated) performance indices at the inspection years and the ideal performance indices at these specific years. Comparing an updated curve to an ideal curve (proved by mathematics only) is the purpose of evaluating the Verification Indicator. Table 5.23 shows the calculation of the VI for the selected systems in the STM Sub-Network.

Table 5.23 shows a VI for stations that were renovated in 2005 (refer to 'Reno-Station II' program) between 0.42 and 0.67. Whereas the VI for the tunnels and auxiliary structures varies between 0.89 and 0.93. Thus, it can be stated that the SUPER model shows performance indices 33% to 58% lower than the ideal performance curve (i.e. following exactly the inverse of the Weibull reliability cummulative function) for systems heavily deteriorated and made up of lots of components. But for systems that do not show a big loss of performance, the ideal and the predicted performance factors have only 10% difference on average. In addition, the systems that contain a large number of components show a bigger difference between the Ideal and Predicted performance indices.

Table 5.23 SUPER Model Verification Indicator

System	Year	MPI	IPI	VI
STA1	2005	0.61	0.91	0.67
TUN1	2004	0.85	0.92	0.92
AS1	1996	0.95	0.96	0.98
TUN2	2004	0.82	0.92	0.89
STA3	2005	0.61	0.91	0.67
TUN3	2004	0.82	0.92	0.89
STA4	2005	0.39	0.91	0.42
TUN4	2004	0.82	0.92	0.89
AS4	1995	0.90	0.96	0.93
STA5	2005	0.46	0.91	0.50
TUN5	2004	0.83	0.92	0.90
STA6	2005	0.53	0.91	0.58

5.6 SUMMARY

This chapter covers the SUPER model results based upon the evaluation of different cracks and defects' weights using the Analytic Hierarchy Process technique. The SUPER model is then implemented on a segement of the STM network, designated by the STM Sub-Network. First, the STM Sub-Network hierarchy is defined. The performance assessment for different components are evaluated and tabulated. The components integrated performance curves are constructed. Next, the systems integrated performance curves are constructed. Finally, the lines and the Sub-Network integrated performance curves are constructed. A specific case study is performed, where the integrated performance indices of years 2011 and 2021 for the systems, lines and Sub-Network are retreived from the performance curves and analyzed.

Several sensitivity analyses are performed using three categories. The first category analyzed the sensitivity of the performance curve to the construction year. The second category analyzed the sensitivity of the performance curve to the change of the cracks and defects weights. The last one analyzed the sensitivity of the performance index to the change in the cracks and defects scores. The model is tested using two methods: the first is based on comparing the performance curve to real situations; and the second is based on comparing the predicted (or updated) system performance curve to the ideal performance curve, by using a verification index.

CHAPTER 6: THE SUPER MODEL SOFTWARE

6.1 INTRODUCTION

An automated (software) application of the SUPER model is developed in order to make the model accessible and usable by the managers of transit authorities. The software should be easy and quick in usage, accurate and easy to update, easy to communicate, adaptable, supported by data, acceptable to practitioners and clients alike, and have a flexible level of sophistication.

The original SUPER model calculations are performed in an ‘Excel’ file. The software application is called the ‘SUPER MODEL SOFTWARE’. It is an application file (*.exe*) that can be uploaded to any transit authority web site. It is developed using the C++ programming language. The SUPER Model Software is a generic software application that can be used by any transit authority and is not bounded by a number of systems and lines in a network. However the only limitation is the number of floors, which is set to a maximum of four per station.

Figure 6.1 shows the SUPER Model Software application flow chart. The SUPER Model Software starts by inputting the network information on one hand, and the inspection information from the inspection reports. The network information can be stored in a ‘.XML’ document file; however the inspection information must be retrieved, filtered and sorted in a separate ‘Excel’ file before using the SUPER Model Software application. The SUPER Model Software next runs the application automatically, and the results and performance curves of the network hierarchy are displayed in windows. The transit manager can retrieve and use any output information (performance indices and curves) for the M&R planning and asset management.

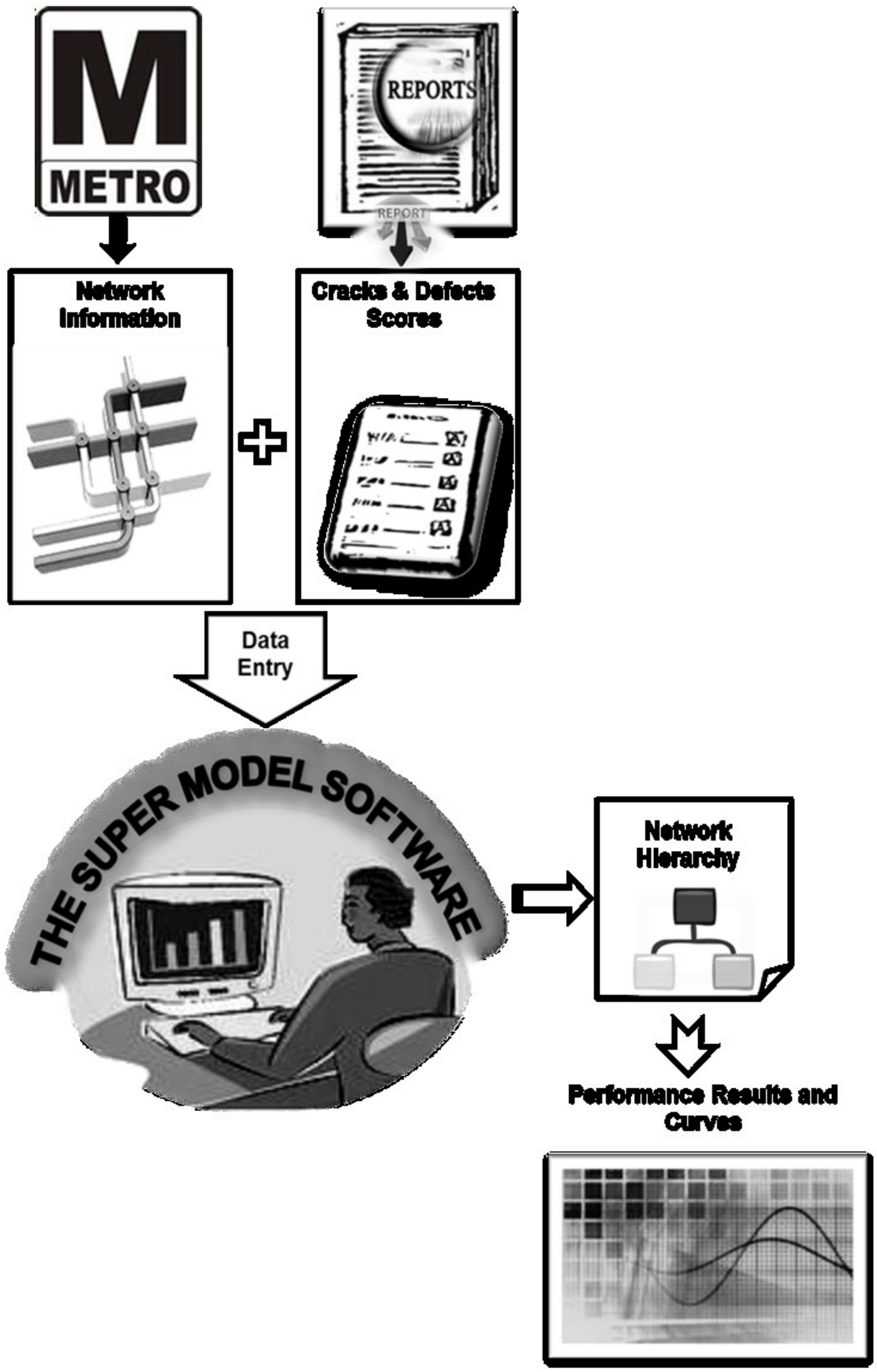


Figure 6.1 The SUPER Model Software Flow Chart

6.2 THE SUPER MODEL SOFTWARE INPUT

The SUPER Model Software main skeleton follows the network hierarchy. The user starts by running the SUPER Model Software application file. The starting window is the '*identification'* window, where the user enters the network name, and the number of lines in the network as illustrated in the snapshot Figure 6.2. This window clarifies that the model used in the application is the SUPER model. Furthermore, saved '.XML' document files from previous inspections and runs can be imported.

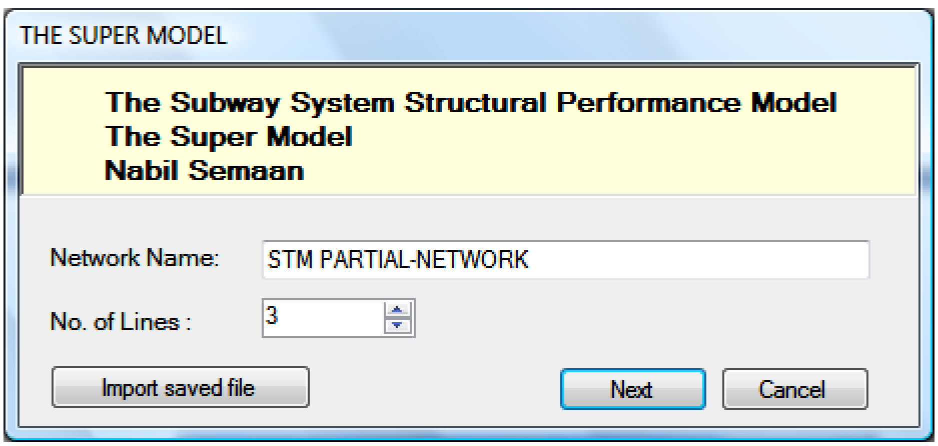


Figure 6.2 The SUPER Model Software *Identification* Window Snapshot

By selecting 'Next', the user is faced with the main '*hierarchy and information*' window. In this window, and for each line, the user inputs the information pertaining to each system, as illustrated in Figure 6.3. Figure 6.3 shows a snapshot of the main '*hierarchy and information*' window for 'Line 1' (Orange line) stations. In this particular window, three main buttons indicate the type of system the user can input: stations, tunnels and auxiliary structures. The user starts with one system, and can add systems as required. Figure 6.3 illustrates the entries for the stations analyzed in the SUPER model implementation, i.e. STA1 to STA3 for the Orange line. The same can be done for the tunnels and auxiliary structures of the Orange line. For each station (Figure 6.3 as an example), the name, code, number of floors, construction year, last inspection year and the M&R year are entered.

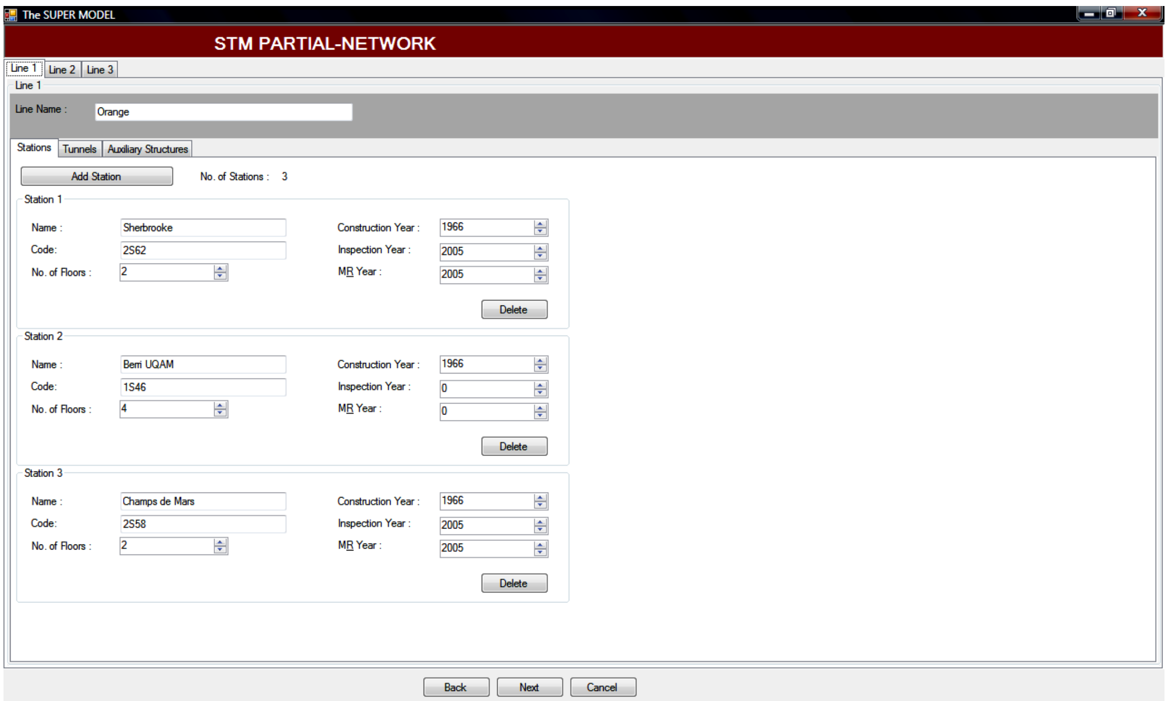


Figure 6.3 Orange Line Stations *Hierarchy and Information* Window Snapshot

The same input is repeated for the tunnels and auxiliary structures of the Orange line. Moreover, by choosing the 'Line2' and 'Line3' button at the top right of the '*hierarchy and information*' window, the user can input the hierarchy information for lines 2 and 3 of the network. By selecting 'Next', the user is directed towards the main '*Data/Results/Graph*' window. This same window comprises the inspection cracks and defects scores input in the '*Data*' window, and the output in both the '*Results*' window and the '*Graph*' window. At the left hand side of this

'*Data/Results/Graph*' window the complete network hierarchy is illustrated. The user starts by selecting the system, line or network desired from the left hand side of the hierarchy, and instantaneously the scores data entry, the '*Results*' and the '*Graph*' windows, are opened. Figure 6.4 illustrates a snapshot of the '*Data*' window of the first station in the Orange line, STA1 or 'Sherbrooke' station.

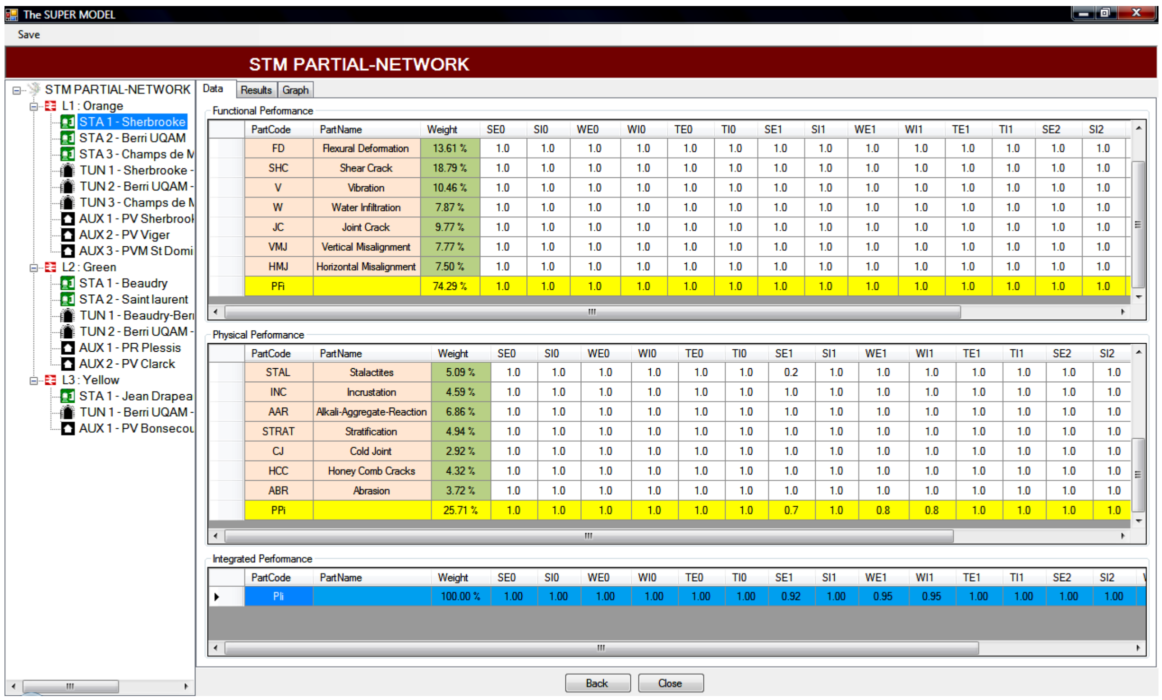


Figure 6.4 Station STA1 *Data* Window Snapshot

6.3 THE SUPER MODEL SOFTWARE OUTPUT

The SUPER model calculation of results and construction of the performance curves are done automatically in the software. The user can go to the '*Results*' and '*Graph*' windows to read the performance index per year and look at the performance curve respectively. Figures 6.5 and 6.6 illustrate snapshots of the STA1 station '*Results*' and '*Graph*' window, respectively. In the '*Results*' window, the transit manager reads the integrated performance index for all the components in the system, and for each year spanning from the construction year to the service life (and beyond, 100 years from the construction years). The user reads the system (station STA1 in the following Figure 6.5) integrated performance index for the different years. The user can also read the performance curve of the system (station STA1 in the following Figure 6.6) in the '*Graph*' window.

The user can next shift to a higher level of the network hierarchy by choosing the corresponding button for the desired line. At the line level, the user can only read the performance index results in the '*Results*' window, and the performance curve in the '*Graph*' window. Figure 6.7 illustrates a snapshot of the 'Orange' line (Line 1) '*Graph*' window. The '*Results*' and '*Graph*' windows have the same shape and format as the systems windows.

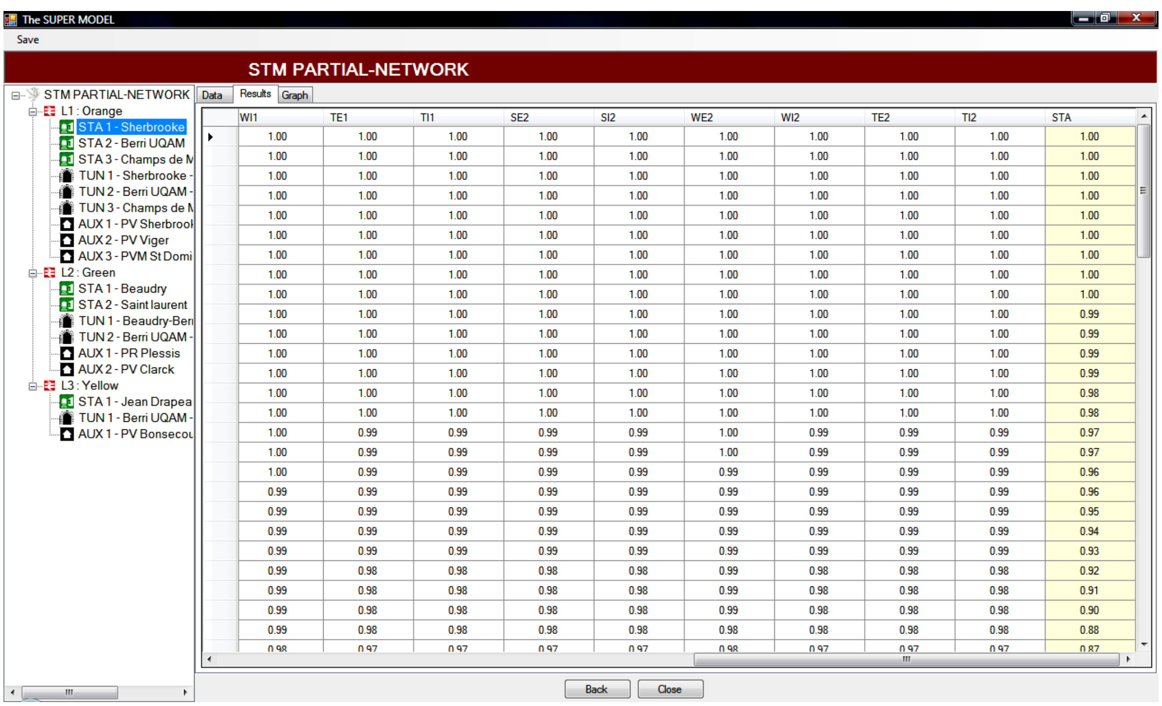


Figure 6.5 Station STA1 *Results* Window Snapshot

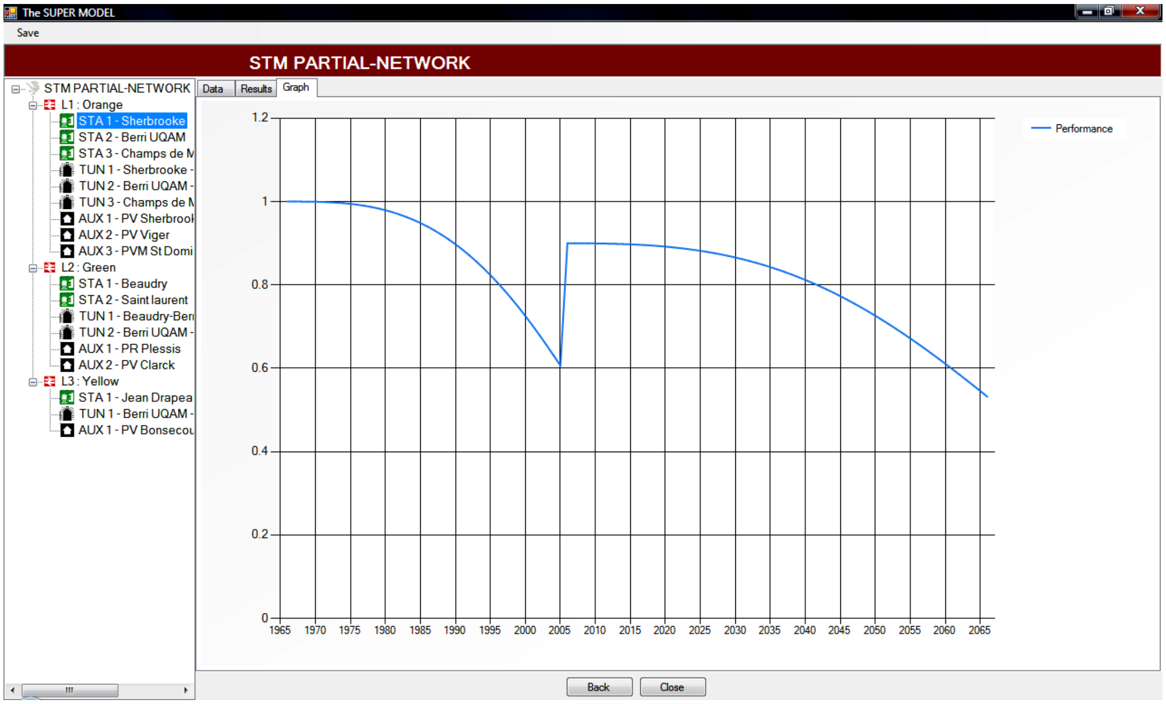


Figure 6.6 Station STA1 *Graph* Window Snapshot

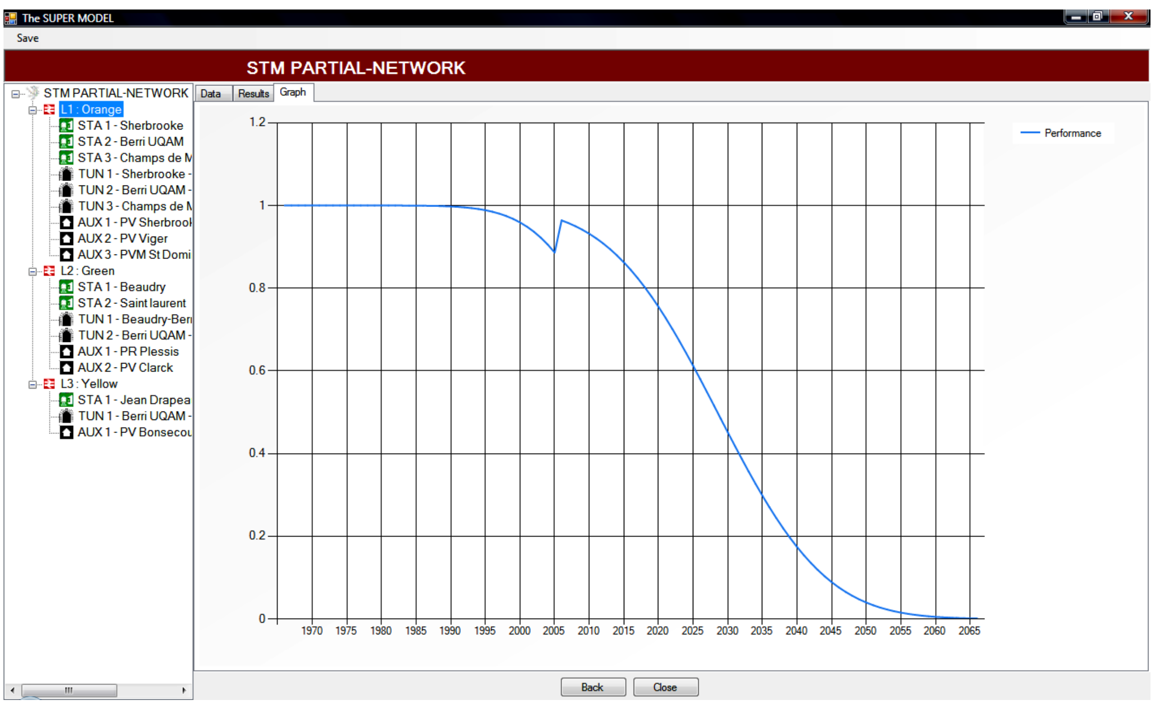


Figure 6.7 Orange Line *Graph* Window Snapshot

The results and performance curves of the other lines can be easily read. Finally, by clicking on the network level icon on the left hand side of the hierarchy window, the network '*Results*' and '*Graph*' windows are shown. The results or the integrated performance indices for the different years are shown in the 'Results' window. Similarly, the network integrated performance curve (STM Sub-Network in the following figure) is shown the '*Graph*' window snapshot, as illustrated in Figure 6.8.

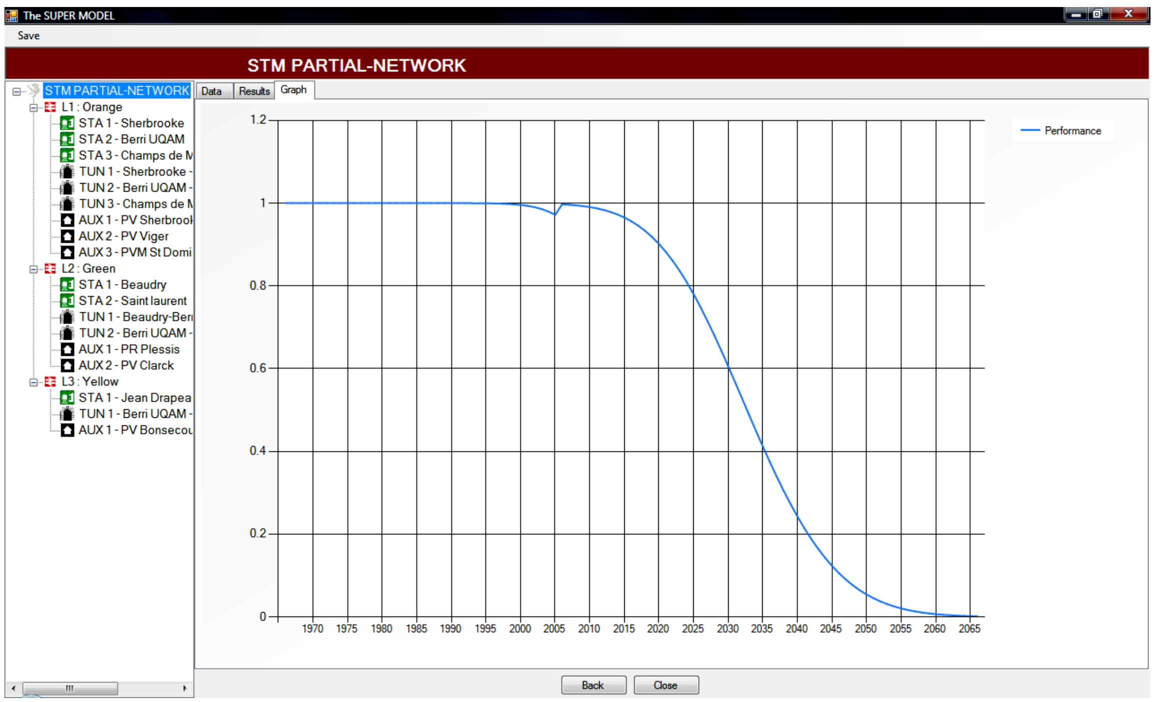


Figure 6.8 STM Sub-Network *Graph* Window Snapshot

6.4 SUMMARY

A software of the SUPER model is developed, entitled the 'SUPER Model Software'. The SUPER Model Software is an application which is user friendly, quick to use, and easy to update. The software starts by entering the network hierarchy and information, and the inspection information. The software automatically evaluates the performance indices and constructs the performance curves of the systems, lines and the network. Snapshots of the different inputs and outputs are shown in this chapter.

CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

7.1 SUMMARY AND CONCLUSIONS

7.1.1 Summary

Communities increase their demand for a higher quality of life where people move freely with an affordable, reliable and efficient public transit. Therefore, careful planning and management for a safe public transit structure are crucial. Plans consist of assessing structural network performance, predicting future performance, planning future maintenance and repair policies and optimizing future budget allocation. Thus, the focus of this research is in the development of the SUbway PERformance (SUPER) model, which assesses structural performance of different components in a subway network and develops performance curves of subway components, systems, lines and the entire network. The SUPER model assesses the physical and functional performance indices for components using visual inspection scores of structural cracks and defects. The cracks and defects weights are evaluated using the Analytic Hierarchy Process method. The physical and functional performance indices are combined using the Multi-Attribute Utility Theory and an integrated performance index (P_I) is determined for each component. The SUPER model evaluates an ideal performance curve using the cumulative reliability Weibull function for each one of the components. Using the P_I evaluated from the inspection reports, the ideal performance curves are updated, and a predicted performance curve is evaluated. Then, a performance model for each system is evaluated using series/parallel system modeling technique, and a performance curve is constructed for each system. Using the series/parallel system modeling technique in order to develop a line performance model, a performance curve for each line is constructed. Finally, using the series/parallel system modeling technique in order to evaluate a network performance model, the network performance curve is constructed.

7.1.2 Conclusions

Data used in the SUPER model are gathered using two techniques: inspections *direct data retrieval* and *questionnaires*. Several conclusions can be drawn as follows:

- The most frequent defect in STM structural components is the ‘secondary cracks’, appearing 1029 times in twelve (12) stations. The second defect is ‘efflorescence’ (406 times in twelve stations).
- In twelve STM stations, 1599 defects are found compared to 40 structural cracks. This means that the STM structures are properly designed and constructed. However harsh external environment affects greatly the structural components.

The SUPER model is implemented to a segment of STM network, the ‘STM Sub-Network’. The following main conclusions can be drawn:

- **Cracks and defects' weights**: the ‘continued movement’ and ‘shear cracks’ are the two most important structural cracks, with weights of 21.51% and

18.79% respectively. They are followed closely by the ‘flexural deformation’ structural crack (13.61% weight). On the other hand, ‘rebar corrosion’ and secondary ‘cracks’ are the most important defects, with weights of 14.95% and 11.40% respectively. They are followed by ‘efflorescence’ and ‘disintegration’, with weights of 9.33% and 9.19% respectively. Finally, the functional performance is found 3 times more important than the physical performance.

- **Performance of Stations**: the steady state value of the STM Sub-Network stations are either 7 or 8 years on the average. After that, the stations deteriorate at an average rate between 2% and 3%. Moreover, the useful service life of the stations is year 2076, i.e. 110 years after construction due to the maintenance action performed in 2005.

- **Performance of Tunnels**: the steady state value of the STM Sub-Network tunnels are 11 years. The tunnels deteriorate at an average rate of 2%. Furthermore, the useful service life of the tunnels varies between years 2029 and 2033, i.e. a minimum of 63 years after construction.

- **Performance of Auxiliary structures**: the steady state value of the STM Sub-Network auxiliary structures vary between 10 and 14 years. The auxiliary structures deteriorate at a rate of 2%. In addition, the useful service life of the auxiliary structures varies between years 2024 and 2040, i.e. a minimum of 58 years after construction.

- **Performance of Lines**: the steady state values of the segment of the Orange line and Green line are 26 years and 17 years respectively. While, the steady state of the segment of the Yellow line is 6 years. The average deterioration rate of the lines is 2.5%. The useful service life of the segment of the Orange line is year 2041, 75 years after construction. The useful service life of the segment of the Green line is year 2032, i.e. 66 years from construction. While, the service life of the segment of the Yellow line is year 2015, i.e. 49 years from construction only.

- **Performance of Sub-Network**: The steady state value of the STM Sub-Network is 34 years. The network deteriorates at a rate of 3.5%. The useful service life is year 2045, and the service life is year 2052.
- **Sensitivity analysis**: A sensitivity analysis for the effect of the year of construction on the performance curve shows that the smaller the difference between the construction and inspection year, the higher the deterioration rate. Stations constructed in 1982 and inspected in 1996 have a deterioration rate of 4.5%. Sensitivity analysis on the effect of the cracks and defects weights on the performance curves show that if cracks and defects weights change ±40%, the performance changes between ±16% to ±25%, the useful service life changes ±5% on the average, and the service life changes ±5% on the average. Sensitivity analysis on the effect of the cracks and defects scores on the performance curves show that if cracks and defects scores change down to -40%, the performance drops to -15% on the average.
- **The SUPER model testing** shows that the model matches real situations as in the case of 'Côte Ste Catherine' station. In addition, the SUPER model testing shows that the discrepancy between the stations' updated curves and ideal

performance curves range from 33% to 58%. The discrepancy between the updated and an ideal performance curve for tunnels and auxiliary structures is only 10%.

7.2 RESEARCH CONTRIBUTIONS

The SUPER model contributes to the better solution of the threefold problem of subway network performance modeling: (i) lack of integration of condition and safety in a unique deterioration model, (ii) limited scope of existing subway models, and (iii) inappropriate existing infrastructure mathematical deterioration models. Therefore, the SUPER model considers both the particularity (few inspections) and complexity (lot of different components) of subway networks. The SUPER presents important contributions in the field of subway network asset (infrastructure) management because it:

- Assesses the physical and functional performance of the subway network components and develops an integrated performance index for each.
- Develops integrated performance curves for the components using ideal curves that are updated with the available inspections.
- Develops integrated performance curves of stations, tunnels, and auxiliary structures on each subway line in the network.
- Develops integrated performance curves for lines in addition to the entire network.
- Develops the SUPER Model software application, based on the SUPER model methodology. The SUPER Model Software application allows

subway transit managers to develop performance models and curves for the systems, lines and network in the subway network.

7.3 RESEARCH LIMITATIONS

The SUPER model has the following assumptions and limitations:

- Existing M&R actions are assumed to affect the whole station, not each component separately. Furthermore, the model assumes that the maximum improvement of the performance due to major M&R action is 0.9.
- The main limitation of SUPER model implementation lies in testing and/or validation processes. New inspections must be done before a proper model validation is performed.
- The SUPER Model Software application is limited to four floors per station.

7.4 POTENTIAL FUTURE RESEARCH

The potential future research can be divided into two areas: (i) current research enhancement areas, and (ii) future research extension areas. Both area of recommendations for potential future research are described as follows:

7.4.1 Current Research Enhancement Areas

Current research can be enhanced by the following scenarios:

- Collect more data, i.e. more questionnaires and inspection reports. This will increase the sample size for the cracks and defects weights and improve the input data. This will also enhance the model by using probability distributions for the cracks/defects weights instead of using the average values solely. Using stochastic data input and Monte Carlo simulation, new stochastic performance curves can be developed.

- Apply the SUPER model to a large number of transit authorities (other than the STM). This will enhance model testing and validation for additional real cases. Additional input data (chiefly inspection reports) will allow for the development of Markov Chain performance models. Transition probability matrices can be evaluated with little assumptions. Therefore, the SUPER model performance curves can then be compared to the Markov Chain performance curves.
- Incorporate Maintenance and Rehabilitation (M&R) information in the components' performance curves. This will enhance the model implementation to be more practical. In the present research, the SUPER model methodology does not change; however, the implementation better reflects real life. This is considered an improvement for the current SUPER model.
- Develop a web-based software tool, which will enhance the SUPER Model Software application so that unlimited number of station floors can be used on one hand and multi-users can profit from this software on the other.

7.4.2 Future Research Extension Areas

Several future extension areas are summarized briefly as follows:

- The SUPER model can be used in future research in order to develop optimized maintenance and repair plans of subway networks. Future research can focus on the best maintenance plan that improves performance while reducing the life cycle cost. The different M&R actions must be defined (example, rehabilitation, preventive maintenance, full repair, etc…). Then, based on the performance curves, Integer programming, or multi-objective programming (or other optimization techniques) can be used in order to choose between the different M&R actions, such that the performance of components, systems, lines and network is maximized and the life cycle cost is minimized. Budget allocation model can be developed based on the SUPER model results.

- Develop subway network performance models based on non-destructive inspection techniques. Instead of only using visual inspection method, non-destructive assessment methods of the different cracks and defects can be adopted, such as Schmidt hammer, ultrasonic method, electro-magnetic method, liquid penetrant method, radiographic and eddy current methods. Thus, new cracks and defects scoring methodology must be developed using either data mining techniques, fuzzy set theory method, or artificial neural network method. Hence, new performance assessment indices can be evaluated.
- The SUPER model can be used to model the performance of other civil infrastructure that has similar characteristics. The SUPER model is best used if the civil infrastructure hierarchy follows a network format. The infrastructure network hierarchy must be defined first. New performance factors must be defined and developed. However, making use of the advantages of the Weibull function, infrastructure performance curves can be constructed. New

series/parallel systems models that define the specific infrastructure behavior should be developed.

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APPENDIX A

The SUbway PERformance (SUPER) model Questionnaire Sample

Part I. General Information

This survey is part of a research done at Concordia University, Construction and Engineering Management graduate program, under the title: **The SUbway PERformance (SUPER) model**. The purpose of this survey is to analyze the cracks and defects on the performance of the different structural components of subway stations, tunnels and auxiliary structures, and rate their importance relative to each other.

In order to ensure confidentiality, your company information will not be linked in any way to the questions in the subsequent sections. You may respond anonymously if you wish. *Would you like your company name acknowledged as a participant in this research?*

☐**Yes** ☐**No**

Name of the Company	
Location of the Company	
Name of the Respondent	
Title of the Respondent	
Years of Experience	

Part II. Comparison between the structural cracks

Any structural component not functioning well is subject to lot of internal and external factors. The results of any structural deficiency are structural cracks that appear on the component. Some cracks are due to design deficiencies, and some are due to construction deficiencies. The following table describes the structural cracks that appear on the components within each category:

Design- based Structural Cracks	Description
1. SM	Stable Movement of the component
2. CM	Continued (underway) increasing movement of the component
3. FD	Flexural deformation of the component
4. SHC	Shear crack in the component

5. V	Considerable vibration of the component
Construction-based Structural Cracks	**Description**
1. W	Water infiltration in the component
2. JC	Joint crack
3. VMJ	Vertical misalignment of joint
4. HMJ	Horizontal misalignment of joint

The information gathered from this part of the survey will be used to model the importance of each crack relative to the whole set of structural cracks. The following questions require a pair-wise comparison between the different cracks using the preference/importance scale shown below. The cracks are shown in tables-matrices; using the scale of importance please assign subjectively at each relevant space in the table-matrix a number scale, which describes the relative importance of a specific crack with respect to the others.

Comparison Scale	
9	Extremely More Important
7	Very Strongly More Important
5	Strongly More Important
3	Slightly Important
1	Equally Important
1/3	Slightly Less Important
1/5	Strongly Less Important
1/7	Very Strongly Less Important
1/9	Extremely Less Important

<u>Part II. A</u>

First a comparison matrix between the design-based cracks and construction-based cracks should be filled-in. Compare the following <u>cracks categories</u> with respect to the others

►►	Design-based Cracks	Construction-based Cracks
Design-based Cracks	1	
Construction-based Cracks		1

Part II.B

Second, a comparison matrix between the different design-based cracks should be filled-in. Compare the following cracks with respect to the others:

Design-based Cracks:

►►	SM	CM	FD	SHC	V
SM	1				
CM		1			
FD			1		
SHC				1	
V					1

Part II. C

Third, a comparison matrix between the different design-based cracks should be filled-in Compare the following cracks with respect to the others:

Construction-based Cracks:

►►	W	JC	VMJ	HMJ
W	1			
JC		1		
VMJ			1	
HMJ				1

Part III. Comparison between the structural defects

Any structural component that has a deteriorated physical condition is subject to lot of external factors. The results of any non-structural deficiency are structural defects that appear on the component. Some defects are due to chemical attack, and some are due to mechanical/physical attack. The following table describes the structural defects that appear on the components within each category:

Chemical- based Structural Cracks	**Description**
1. RCOR	Rebar corrosion
2. DEL	Delamination or separation
3. SWE	Sweating on the concrete surface
4. DIS	Disintegration
5. STAL	Stalactites, or crystal formation
6. INC	Incrustation
7. AAR	Alkali-Aggregate-Reaction
8. STRAT	Stratification
Mechanical-based Structural Cracks	**Description**
1. C	Cracks (secondary)
2. EFFL	Efflorescence
3. SEGR	Segregation
4. SCA	Scaling of concrete
5. ER	Erosion
6. CJ	Construction Joint
7. HCC	Honey Comb cracks
8. ABR	Abrasion

The information gathered from this part of the survey will be used to model the importance of each defect relative to the whole set of structural defects. The following questions require a pair-wise comparison between the different defects using the preference/importance scale shown below. The defects are shown in tables-matrices; using the scale of importance please assign subjectively at each relevant space in the table-matrix a number scale, which describes the relative importance of a specific defect with respect to the others.

Comparison Scale	
9	Extremely More Important
7	Very Strongly More Important
5	Strongly More Important
3	Slightly Important
1	Equally Important
1/3	Slightly Less Important
1/5	Strongly Less Important
1/7	Very Strongly Less Important
1/9	Extremely Less Important

Part III. A

First a comparison matrix between the chemical-based defects and the mechanical-based defects should be filled-in. Compare the following defects categories with respect to the others:

►►	**Chemical-based defects**	**Mechanical-based defects**
Chemical-based defects	1	
Mechanical-based defects		1

Part III.B

Second, a comparison matrix between the different chemical-based defects should be filled-in. Compare the following defects with respect to the others:

Chemical-based Defects:

►►	RCOR	DEL	SWE	DIS	STAL	INC	AAR	STRAT
RCOR	**1**							
DEL		**1**						
SWE			**1**					
DIS				**1**				
STAL					**1**			
INC						**1**		
AAR							**1**	
STRAT								**1**

Part III. C

Third, a comparison matrix between the different mechanical-based defects should be filled-in. Compare the following defects with respect to the others:

Mechanical-based Defects:

►►	C	EFFL	SEGR	SCA	ER	CJ	HCC	ABR
C	**1**							
EFFL		**1**						
SEGR			**1**					
SCA				**1**				
ER					**1**			
CJ						**1**		
HCC							**1**	
ABR								**1**

Part IV. Comparison between the functional and physical performance states

A structural component performance state, which changes during time in service, is reflected by two different indicators: the “physical condition state”, and the “functionality state”. The “physical condition state” relates to a component’s general ‘physical fitness’, independent of its mission, as it deteriorates due to routine aging, excessive or abusive use, or poor maintenance. The “functionality state” relates to the component suitability to function as intended and required for the mission. The “functionality state” is distinct from, and determined independently from the “physical condition state”.

The information gathered from this part of the survey will be used to model the importance of each state relative to the whole set of state. The following questions require a pair-wise comparison between the different states using the preference/importance scale shown below. The states are shown in tables-matrices; using the scale of importance please assign subjectively at each relevant space in the table-matrix a number scale, which describes the relative importance of a specific states with respect to the others.

Comparison Scale	
9	Extremely More Important
7	Very Strongly More Important
5	Strongly More Important
3	Slightly Important
1	Equally Important
1/3	Slightly Less Important
1/5	Strongly Less Important
1/7	Very Strongly Less Important
1/9	Extremely Less Important

Compare the following <u>states</u> with respect to the others:

►►	Physical Condition State	Functionality State
Physical Condition State	**1**	
Functionality State		**1**

Thank you for your participation…

APPENDIX B

SUPER MODEL IMPLEMENTATION TO STM

Detailed Components' Performance Assessment Tables

Table B1 Performance Assessment of STA1 Components

(Inspection 2005)

	Weight (W_S)	Score (S_S)																	
		Level 0						Level 1						Level 2					
		SE0	SI0	WE0	WI0	TE0	TI0	SE1	SI1	WE1	WI1	TE1	TI1	SE2	SI2	WE2	WI2	TE2	TI2
SM	2.71%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
CM	21.51%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
FD	13.61%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
SHC	18.79%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
V	10.46%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
W	7.87%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
JC	9.77%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
VMJ	7.77%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
HMJ	7.50%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
P_{Fi}	74.29%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
RCOR	14.95%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
C	11.40%	1.0	1.0	1.0	1.0	1.0	1.0	0.2	1.0	0.2	0.2	1.0	1.0	1.0	1.0	0.4	1.0	1.0	1.0
EFFL	9.33%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.4	1.0	1.0	1.0
SEGR	5.72%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
SCA	4.99%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
DEL	5.62%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
SWE	2.42%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.4	1.0	1.0	1.0
DIS	9.19%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
ER	3.94%	1.0	1.0	1.0	1.0	1.0	1.0	0.2	1.0	1.0	0.4	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
STAL	5.09%	1.0	1.0	1.0	1.0	1.0	1.0	0.6	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
INC	4.59%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
AAR	6.86%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
STRAT	4.94%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
CJ	2.92%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.4	1.0	1.0	1.0
HCC	4.32%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
ABR	3.72%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
P_{Pi}	25.71%	1.00	1.00	1.00	1.00	1.00	1.00	0.76	1.00	0.83	0.80	1.00	1.00	1.00	1.00	0.79	1.00	1.00	1.00
P_{Ii}	**100.00%**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**0.93**	**1.00**	**0.95**	**0.95**	**1.00**	**1.00**	**1.00**	**1.00**	**0.94**	**1.00**	**1.00**	**1.00**

Table B2 Performance Assessment of STA2 Components

	Weight	Score (S_S)																													
		Level 0						Level 1						Level 2						Level 3						Level 4					
	(W_S)	SE0	SI0	WE0	WI0	TE0	TI0	SE1	SI1	WE1	WI1	TE1	TI1	SE2	SI2	WE2	WI2	TE2	TI2	SE3	SI3	WE3	WI3	TE3	TI3	SE4	SI4	WE4	WI4	TE4	TI4
SM	2.71%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
CM	21.51%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
FD	13.61%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
SHC	18.79%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
V	10.46%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
W	7.87%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
JC	9.77%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
VMJ	7.77%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
HMJ	7.50%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
P_{Fi}	74.29%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
RCOR	14.95%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
C	11.40%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
EFFL	9.33%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
SEGR	5.72%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
SCA	4.99%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
DEL	5.62%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
SWE	2.42%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
DIS	9.19%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
ER	3.94%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
STAL	5.09%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
INC	4.59%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
AAR	6.86%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
STRAT	4.94%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
CJ	2.92%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
HCC	4.32%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
ABR	3.72%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
P_{Pi}	25.71%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
P_{Ii}	**100.00%**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**

Table B3 Performance Assessment of STA3 Components

(Inspection 2005)

	Weight	Score (S_S)																	
	(W_S)	Level 0						Level 1						Level 2					
		SE0	SI0	WE0	WI0	TE0	TI0	SE1	SI1	WE1	WI1	TE1	TI1	SE2	SI2	WE2	WI2	TE2	TI2
SM	2.71%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
CM	21.51%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
FD	13.61%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
SHC	18.79%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
V	10.46%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
W	7.87%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
JC	9.77%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
VMJ	7.77%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
HMJ	7.50%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
P_{Fi}	74.29%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
RCOR	14.95%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
C	11.40%	1.0	1.0	1.0	1.0	1.0	1.0	0.4	0.2	0.4	0.2	1.0	1.0	0.2	1.0	1.0	0.2	1.0	1.0
EFFL	9.33%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.8	0.8	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
SEGR	5.72%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
SCA	4.99%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.2	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
DEL	5.62%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
SWE	2.42%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.6	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
DIS	9.19%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
ER	3.94%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
STAL	5.09%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
INC	4.59%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
AAR	6.86%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.6	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
STRAT	4.94%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
CJ	2.92%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.2	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
HCC	4.32%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
ABR	3.72%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
P_{Pi}	25.71%	1.0	1.0	1.0	1.0	1.0	1.0	0.90	0.82	0.88	0.69	1.00	1.00	0.83	1.00	1.00	0.83	1.00	1.00
P_{Ii}	**100.00%**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**0.97**	**0.95**	**0.97**	**0.91**	**1.00**	**1.00**	**0.95**	**1.00**	**1.00**	**0.95**	**1.00**	**1.00**

Table B4 Performance Assessment of STA4 Components

(Inspection 2005)

	Weight	Score (S_S)																													
	(W_S)	Level 0						Level 1						Level 2						Level 3						Level 4					
		SE0	SI0	WE0	WI0	TE0	TI0	SE1	SI1	WE1	WI1	TE1	TI1	SE2	SI2	WE2	WI2	TE2	TI2	SE3	SI3	WE3	WI3	TE3	TI3	SE4	SI4	WE4	WI4	TE4	TI4
SM	2.71%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
CM	21.51%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.40	0.40	0.40	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
FD	13.61%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.60	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
SHC	18.79%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
V	10.46%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
W	7.87%	0.60	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.40	1.00	0.60	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
JC	9.77%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.60	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
VMJ	7.77%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
HMJ	7.50%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
P_{Fi}	74.29%	0.96	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.93	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.76	0.82	0.79	0.95	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
RCOR	14.95%	1.00	1.00	1.00	1.00	1.00	1.00	0.80	1.00	1.00	0.80	1.00	1.00	0.80	1.00	1.00	1.00	0.60	1.00	0.80	1.00	0.80	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
C	11.40%	0.60	1.00	0.60	0.40	1.00	1.00	0.40	1.00	0.20	0.20	1.00	1.00	0.40	1.00	1.00	1.00	0.60	1.00	0.20	0.20	0.60	0.20	0.40	1.00	1.00	1.00	0.40	1.00	1.00	1.00
EFFL	9.33%	1.00	1.00	0.60	0.80	1.00	1.00	0.60	1.00	1.00	1.00	1.00	1.00	0.80	1.00	1.00	1.00	0.60	1.00	0.60	1.00	0.60	0.80	0.40	1.00	0.40	1.00	1.00	1.00	1.00	1.00
SEGR	5.72%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
SCA	4.99%	1.00	1.00	0.80	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
DEL	5.62%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.80	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.40	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
SWE	2.42%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.80	0.80	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
DIS	9.19%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.60	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
ER	3.94%	1.00	1.00	1.00	1.00	1.00	1.00	0.40	1.00	1.00	0.80	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.60	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
STAL	5.09%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.20	1.00	1.00	1.00	1.00	1.00
INC	4.59%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
AAR	6.86%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
STRAT	4.94%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.80	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
CJ	2.92%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
HCC	4.32%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.60	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
ABR	3.72%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
P_{Pi}	25.71%	0.94	1.00	0.89	0.88	1.00	1.00	0.80	1.00	0.83	0.80	1.00	1.00	0.85	0.95	1.00	1.00	0.83	1.00	0.77	0.83	0.82	0.82	0.83	1.00	0.85	1.00	0.90	1.00	1.00	1.00
P_{Ii}	**100.0%**	**0.96**	**1.00**	**0.97**	**0.97**	**1.00**	**1.00**	**0.94**	**1.00**	**0.95**	**0.90**	**1.00**	**1.00**	**0.96**	**0.99**	**1.00**	**1.00**	**0.95**	**1.00**	**0.76**	**0.82**	**0.80**	**0.91**	**0.95**	**1.00**	**0.96**	**1.00**	**0.97**	**1.00**	**1.00**	**1.00**

Table B5 Performance Assessment of STA5 Components

(Inspection 2005)

	Weight (W_S)	Score (S_S)																							
		Level 0						Level 1						Level 2						Level 3					
		SE0	SI0	WE0	WI0	TE0	TI0	SE1	SI1	WE1	WI1	TE1	TI1	SE2	SI2	WE2	WI2	TE2	TI2	SE3	SI3	WE3	WI3	TE3	TI3
SM	2.71%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
CM	21.51%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
FD	13.61%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.6	1.0	1.0
SHC	18.79%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
V	10.46%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
W	7.87%	1.0	1.0	1.0	1.0	1.0	1.0	0.6	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
JC	9.77%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
VMJ	7.77%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
HMJ	7.50%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
P_{Fi}	74.29%	1.00	1.00	1.00	1.00	1.00	1.00	0.96	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.93	1.00	1.00
RCOR	14.95%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
C	11.40%	1.00	1.00	1.00	1.00	1.00	1.00	0.20	1.00	0.20	1.00	1.00	1.00	0.20	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.60	1.00	1.00
EFFL	9.33%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.40	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
SEGR	5.72%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
SCA	4.99%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
DEL	5.62%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
SWE	2.42%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.40	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
DIS	9.19%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
ER	3.94%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
STAL	5.09%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
INC	4.59%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.40	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
AAR	6.86%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
STRAT	4.94%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
CJ	2.92%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
HCC	4.32%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.40	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.40	1.00	1.00
ABR	3.72%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
P_{Pi}	25.71%	1.00	1.00	1.00	1.00	1.00	1.00	0.83	1.00	0.75	1.00	1.00	1.00	0.76	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.91	1.00	1.00
P_{Ii}	100.00%	1.00	1.00	1.00	1.00	1.00	1.00	0.93	1.00	0.93	1.00	1.00	1.00	0.93	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.93	1.00	1.00

Table B6 Performance Assessment of STA6 Components

(Inspection 2005)

	Weight (W_S)	Score (S_S)																	
		Level 0						Level 1						Level 2					
		SE0	SI0	WE0	WI0	TE0	TI0	SE1	SI1	WE1	WI1	TE1	TI1	SE2	SI2	WE2	WI2	TE2	TI2
SM	2.71%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
CM	21.51%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
FD	13.61%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
SHC	18.79%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
V	10.46%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
W	7.87%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.40	0.40	0.60	0.40	1.00	1.00	0.40	0.40	0.40	1.00	1.00
JC	9.77%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
VMJ	7.77%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
HMJ	7.50%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
P_{Fi}	74.29%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.93	0.93	0.96	0.93	1.00	1.00	0.93	0.93	0.93	1.00	1.00
RCOR	14.95%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
C	11.40%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.20	0.20	1.00	0.20	1.00	1.00	0.20	0.20	0.20	1.00	1.00
EFFL	9.33%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.40	0.40	0.40	1.00	1.00	1.00	0.60	1.00	1.00	1.00	1.00
SEGR	5.72%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.60	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
SCA	4.99%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
DEL	5.62%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
SWE	2.42%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.40	0.60	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
DIS	9.19%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
ER	3.94%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
STAL	5.09%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
INC	4.59%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.60	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
AAR	6.86%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
STRAT	4.94%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
CJ	2.92%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
HCC	4.32%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.60	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
ABR	3.72%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
P_{Pi}	25.71%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.76	0.75	0.84	0.83	1.00	1.00	0.79	0.83	0.83	1.00	1.00
P_{Ii}	**100.00%**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**0.88**	**0.88**	**0.93**	**0.90**	**1.00**	**1.00**	**0.89**	**0.90**	**0.90**	**1.00**	**1.00**

Table B7 Performance Assessment of TUN1 Components

(Inspection 2004)

	Weight (W_S)	Score (S_S) DOME (D)	WALLS (W)	BOTTOM SLAB (BS)
SM	2.71%	1.0	1.0	1.0
CM	21.51%	1.0	1.0	1.0
FD	13.61%	1.0	1.0	1.0
SHC	18.79%	1.0	1.0	1.0
V	10.46%	1.0	1.0	1.0
W	7.87%	1.0	1.0	1.0
JC	9.77%	1.0	1.0	1.0
VMJ	7.77%	1.0	1.0	1.0
HMJ	7.50%	1.0	1.0	1.0
P_{Fi}	74.29%	1.00	1.00	1.00
RCOR	14.95%	1.0	1.0	1.0
C	11.40%	0.4	0.6	1.0
EFFL	9.33%	0.6	0.6	1.0
SEGR	5.72%	1.0	1.0	1.0
SCA	4.99%	1.0	1.0	1.0
DEL	5.62%	0.6	0.6	1.0
SWE	2.42%	1.0	1.0	1.0
DIS	9.19%	1.0	1.0	1.0
ER	3.94%	1.0	1.0	1.0
STAL	5.09%	1.0	1.0	1.0
INC	4.59%	1.0	1.0	1.0
AAR	6.86%	1.0	1.0	1.0
STRAT	4.94%	1.0	1.0	1.0
CJ	2.92%	0.4	0.6	1.0
HCC	4.32%	1.0	1.0	1.0
ABR	3.72%	1.0	1.0	1.0
P_{Pi}	25.71%	0.84	0.89	1.00
P_{Ii}	**100.00%**	**0.96**	**0.97**	**1.00**

Table B8 Performance Assessment of TUN2 Components

(Inspection 2004)

	Weight (W_S)	Score (S_S)		
		DOME (D)	WALLS (W)	BOTTOM SLAB (BS)
SM	2.71%	1.0	1.0	1.0
CM	21.51%	1.0	1.0	1.0
FD	13.61%	1.0	1.0	1.0
SHC	18.79%	1.0	1.0	1.0
V	10.46%	1.0	1.0	1.0
W	7.87%	1.0	1.0	1.0
JC	9.77%	1.0	1.0	1.0
VMJ	7.77%	1.0	1.0	1.0
HMJ	7.50%	1.0	1.0	1.0
P_{Fi}	74.29%	1.00	1.00	1.00
RCOR	14.95%	1.0	0.8	1.0
C	11.40%	0.2	0.6	1.0
EFFL	9.33%	0.4	0.6	1.0
SEGR	5.72%	1.0	1.0	1.0
SCA	4.99%	1.0	1.0	1.0
DEL	5.62%	0.4	0.6	1.0
SWE	2.42%	1.0	1.0	1.0
DIS	9.19%	1.0	1.0	1.0
ER	3.94%	1.0	1.0	1.0
STAL	5.09%	1.0	1.0	1.0
INC	4.59%	1.0	1.0	1.0
AAR	6.86%	1.0	1.0	1.0
STRAT	4.94%	1.0	1.0	1.0
CJ	2.92%	0.6	0.6	1.0
HCC	4.32%	1.0	1.0	1.0
ABR	3.72%	1.0	1.0	1.0
P_{Pi}	25.71%	0.75	0.86	1.00
P_{Ii}	**100.00%**	**0.93**	**0.96**	**1.00**

Table B9 Performance Assessment of TUN3 Components

(Inspection 2004)

		Score (S_S)		
	Weight (W_S)	DOME (D)	WALLS (W)	BOTTOM SLAB (BS)
SM	2.71%	1.0	1.0	1.0
CM	21.51%	1.0	1.0	1.0
FD	13.61%	1.0	1.0	1.0
SHC	18.79%	1.0	1.0	1.0
V	10.46%	1.0	1.0	1.0
W	7.87%	1.0	1.0	1.0
JC	9.77%	1.0	1.0	1.0
VMJ	7.77%	1.0	1.0	1.0
HMJ	7.50%	1.0	1.0	1.0
P_{Fi}	74.29%	1.0	1.0	1.0
RCOR	14.95%	1.0	0.8	1.0
C	11.40%	0.4	0.4	1.0
EFFL	9.33%	0.4	0.4	1.0
SEGR	5.72%	1.0	1.0	1.0
SCA	4.99%	1.0	1.0	1.0
DEL	5.62%	0.4	0.4	1.0
SWE	2.42%	1.0	1.0	1.0
DIS	9.19%	1.0	1.0	1.0
ER	3.94%	1.0	1.0	1.0
STAL	5.09%	1.0	1.0	1.0
INC	4.59%	1.0	1.0	1.0
AAR	6.86%	1.0	1.0	1.0
STRAT	4.94%	1.0	1.0	1.0
CJ	2.92%	0.6	0.6	1.0
HCC	4.32%	1.0	1.0	1.0
ABR	3.72%	1.0	1.0	1.0
P_{Pi}	25.71%	0.81	0.79	1.00
P_{Ii}	**100.00%**	**0.95**	**0.94**	**1.00**

Table B10 Performance Assessment of TUN4 Components

(Inspection 2004)

	Weight (W_S)	Score (S_S) DOME (D)	WALLS (W)	BOTTOM SLAB (BS)
SM	2.71%	1.0	1.0	1.0
CM	21.51%	1.0	1.0	1.0
FD	13.61%	1.0	1.0	1.0
SHC	18.79%	1.0	1.0	1.0
V	10.46%	1.0	1.0	1.0
W	7.87%	1.0	1.0	1.0
JC	9.77%	1.0	1.0	1.0
VMJ	7.77%	1.0	1.0	1.0
HMJ	7.50%	1.0	1.0	1.0
P_{Fi}	74.29%	1.0	1.0	1.0
RCOR	14.95%	1.0	1.0	1.0
C	11.40%	0.4	0.4	1.0
EFFL	9.33%	0.4	0.4	1.0
SEGR	5.72%	1.0	1.0	1.0
SCA	4.99%	1.0	1.0	1.0
DEL	5.62%	0.6	0.6	1.0
SWE	2.42%	1.0	1.0	1.0
DIS	9.19%	1.0	1.0	1.0
ER	3.94%	1.0	1.0	1.0
STAL	5.09%	1.0	1.0	1.0
INC	4.59%	1.0	1.0	1.0
AAR	6.86%	1.0	1.0	1.0
STRAT	4.94%	1.0	1.0	1.0
CJ	2.92%	0.6	0.6	1.0
HCC	4.32%	1.0	1.0	1.0
ABR	3.72%	1.0	1.0	1.0
P_{Pi}	25.71%	0.81	0.81	1.00
P_{Ii}	**100.00%**	**0.95**	**0.95**	**1.00**

Table B11 Performance Assessment of TUN5 Components

(Inspection 2004)

	Weight (W_S)	Score (S_S) DOME (D)	WALLS (W)	BOTTOM SLAB (BS)
SM	2.71%	1.0	1.0	1.0
CM	21.51%	1.0	1.0	1.0
FD	13.61%	1.0	1.0	1.0
SHC	18.79%	1.0	1.0	1.0
V	10.46%	1.0	1.0	1.0
W	7.87%	1.0	1.0	1.0
JC	9.77%	1.0	1.0	1.0
VMJ	7.77%	1.0	1.0	1.0
HMJ	7.50%	1.0	1.0	1.0
P_{Fi}	74.29%	1.00	1.00	1.00
RCOR	14.95%	1.00	1.00	1.00
C	11.40%	0.40	0.40	1.00
EFFL	9.33%	0.60	0.40	1.00
SEGR	5.72%	1.00	1.00	1.00
SCA	4.99%	1.00	1.00	1.00
DEL	5.62%	0.40	0.80	1.00
SWE	2.42%	1.00	1.00	1.00
DIS	9.19%	1.00	1.00	1.00
ER	3.94%	1.00	1.00	1.00
STAL	5.09%	1.00	1.00	1.00
INC	4.59%	1.00	1.00	1.00
AAR	6.86%	1.00	1.00	1.00
STRAT	4.94%	1.00	1.00	1.00
CJ	2.92%	0.40	0.80	1.00
HCC	4.32%	1.00	1.00	1.00
ABR	3.72%	1.00	1.00	1.00
P_{Pi}	25.71%	0.84	0.82	1.00
P_{Ii}	**100.00%**	**0.96**	**0.95**	**1.00**

Table B12 Performance Assessment of TUN6 Components

	Weight (W_S)	Score (S_S)		
		DOME (D)	WALLS (W)	BOTTOM SLAB (BS)
SM	2.71%	1.0	1.0	1.0
CM	21.51%	1.0	1.0	1.0
FD	13.61%	1.0	1.0	1.0
SHC	18.79%	1.0	1.0	1.0
V	10.46%	1.0	1.0	1.0
W	7.87%	1.0	1.0	1.0
JC	9.77%	1.0	1.0	1.0
VMJ	7.77%	1.0	1.0	1.0
HMJ	7.50%	1.0	1.0	1.0
P_{Fi}	74.29%	1.00	1.00	1.00
RCOR	14.95%	1.00	1.00	1.00
C	11.40%	1.00	1.00	1.00
EFFL	9.33%	1.00	1.00	1.00
SEGR	5.72%	1.00	1.00	1.00
SCA	4.99%	1.00	1.00	1.00
DEL	5.62%	1.00	1.00	1.00
SWE	2.42%	1.00	1.00	1.00
DIS	9.19%	1.00	1.00	1.00
ER	3.94%	1.00	1.00	1.00
STAL	5.09%	1.00	1.00	1.00
INC	4.59%	1.00	1.00	1.00
AAR	6.86%	1.00	1.00	1.00
STRAT	4.94%	1.00	1.00	1.00
CJ	2.92%	1.00	1.00	1.00
HCC	4.32%	1.00	1.00	1.00
ABR	3.72%	1.00	1.00	1.00
P_{Pi}	25.71%	1.00	1.00	1.00
P_{Ii}	**100.00%**	**1.00**	**1.00**	**1.00**

Table B13 Performance Assessment of AS1 Components

(Inspection 1995)

	Weight (W_S)	Score (S_S)		
		WALLS (W)	TOP SLAB (ST)	BOTTOM SLAB (SB)
SM	2.71%	1.0	1.0	1.0
CM	21.51%	1.0	1.0	1.0
FD	13.61%	1.0	1.0	1.0
SHC	18.79%	0.8	1.0	1.0
V	10.46%	1.0	1.0	1.0
W	7.87%	0.8	1.0	1.0
JC	9.77%	1.0	1.0	1.0
VMJ	7.77%	1.0	1.0	1.0
HMJ	7.50%	1.0	1.0	1.0
P_{Fi}	74.29%	0.94	1.00	1.00
RCOR	14.95%	1.0	1.0	1.0
C	11.40%	0.8	1.0	1.0
EFFL	9.33%	1.0	1.0	1.0
SEGR	5.72%	1.0	1.0	1.0
SCA	4.99%	1.0	1.0	1.0
DEL	5.62%	1.0	1.0	1.0
SWE	2.42%	1.0	1.0	1.0
DIS	9.19%	1.0	1.0	1.0
ER	3.94%	1.0	1.0	1.0
STAL	5.09%	1.0	1.0	1.0
INC	4.59%	1.0	1.0	1.0
AAR	6.86%	1.0	1.0	1.0
STRAT	4.94%	1.0	1.0	1.0
CJ	2.92%	1.0	1.0	1.0
HCC	4.32%	1.0	1.0	1.0
ABR	3.72%	1.0	1.0	1.0
P_{Pi}	25.71%	0.97	1.00	1.00
P_{Ii}	**100.00%**	**0.95**	**1.00**	**1.00**

Table B14 Performance Assessment of AS2, AS3, AS5 and AS6 Components

	Weight (W_S)	Score (S_S)		
		WALLS (W)	TOP SLAB (ST)	BOTTOM SLAB (SB)
SM	2.71%	1.0	1.0	1.0
CM	21.51%	1.0	1.0	1.0
FD	13.61%	1.0	1.0	1.0
SHC	18.79%	1.0	1.0	1.0
V	10.46%	1.0	1.0	1.0
W	7.87%	1.0	1.0	1.0
JC	9.77%	1.0	1.0	1.0
VMJ	7.77%	1.0	1.0	1.0
HMJ	7.50%	1.0	1.0	1.0
P_{Fi}	74.29%	1.0	1.0	1.0
RCOR	14.95%	1.0	1.0	1.0
C	11.40%	1.0	1.0	1.0
EFFL	9.33%	1.0	1.0	1.0
SEGR	5.72%	1.0	1.0	1.0
SCA	4.99%	1.0	1.0	1.0
DEL	5.62%	1.0	1.0	1.0
SWE	2.42%	1.0	1.0	1.0
DIS	9.19%	1.0	1.0	1.0
ER	3.94%	1.0	1.0	1.0
STAL	5.09%	1.0	1.0	1.0
INC	4.59%	1.0	1.0	1.0
AAR	6.86%	1.0	1.0	1.0
STRAT	4.94%	1.0	1.0	1.0
CJ	2.92%	1.0	1.0	1.0
HCC	4.32%	1.0	1.0	1.0
ABR	3.72%	1.0	1.0	1.0
P_{Pi}	25.71%	1.0	1.0	1.0
P_{Ii}	**100.00%**	**1.00**	**1.00**	**1.00**

Table B15 Performance Assessment of AS4 Components

(Inspection 1995)

	Weight (W_S)	Score (S_S)		
		WALLS (W)	TOP SLAB (ST)	BOTTOM SLAB (SB)
SM	2.71%	1.0	1.0	1.0
CM	21.51%	1.0	1.0	1.0
FD	13.61%	1.0	1.0	1.0
SHC	18.79%	0.6	0.8	1.0
V	10.46%	1.0	1.0	1.0
W	7.87%	0.6	1.0	1.0
JC	9.77%	1.0	1.0	1.0
VMJ	7.77%	1.0	1.0	1.0
HMJ	7.50%	1.0	1.0	1.0
P_{Fi}	74.29%	0.9	1.0	1.0
RCOR	14.95%	1.0	1.0	1.0
C	11.40%	1.0	0.8	1.0
EFFL	9.33%	1.0	1.0	1.0
SEGR	5.72%	1.0	1.0	1.0
SCA	4.99%	1.0	1.0	1.0
DEL	5.62%	1.0	1.0	1.0
SWE	2.42%	1.0	1.0	1.0
DIS	9.19%	1.0	1.0	1.0
ER	3.94%	1.0	1.0	1.0
STAL	5.09%	1.0	1.0	1.0
INC	4.59%	1.0	1.0	1.0
AAR	6.86%	1.0	1.0	1.0
STRAT	4.94%	1.0	1.0	1.0
CJ	2.92%	1.0	1.0	1.0
HCC	4.32%	1.0	1.0	1.0
ABR	3.72%	1.0	1.0	1.0
P_{Pi}	25.71%	1.00	0.97	1.00
P_{Ii}	**100.00%**	**0.90**	**0.96**	**1.00**

APPENDIX C

SUPER MODEL IMPLEMENTATION TO STM

Components' Integrated Performance Curves

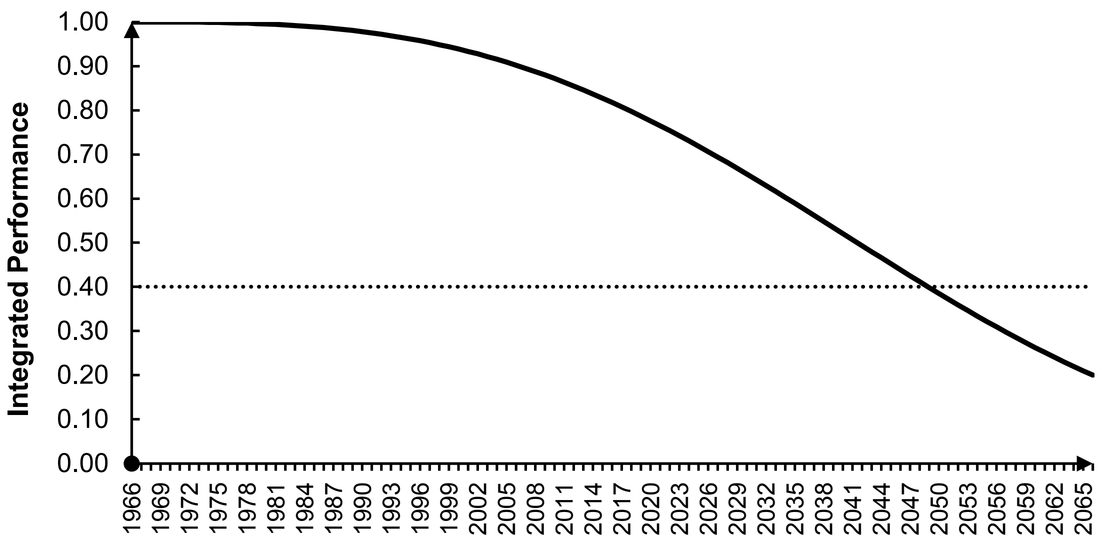

Figure C.1 STA1 Platform Components' Performance Curves

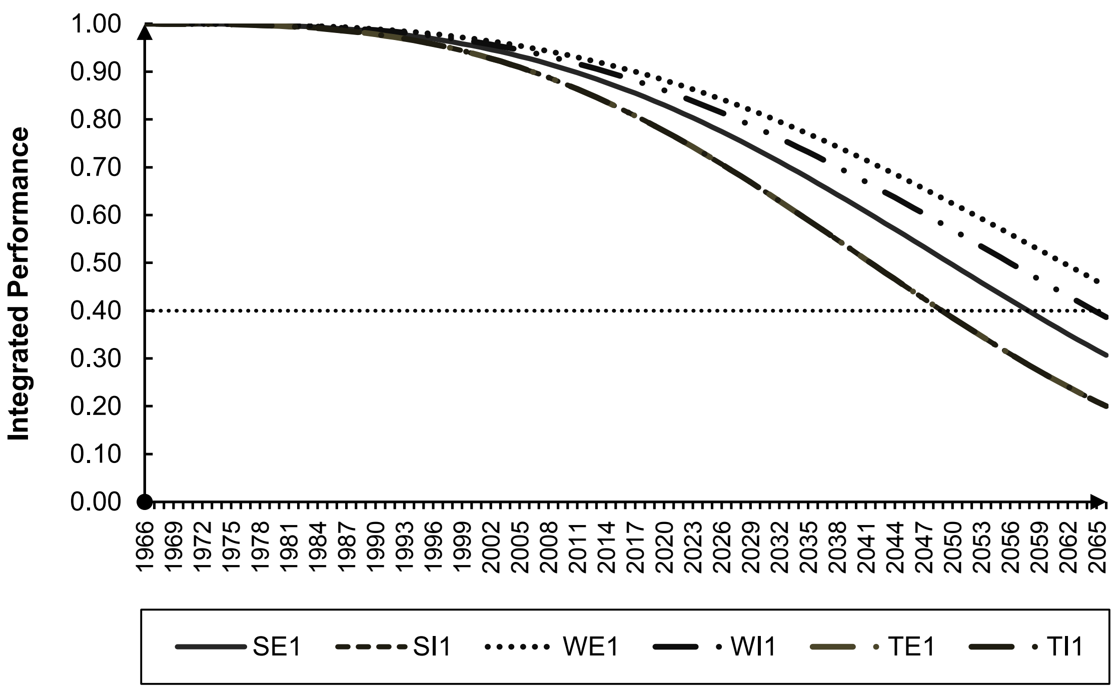

Figure C.2 STA1 1st Floor Components' Performance Curves

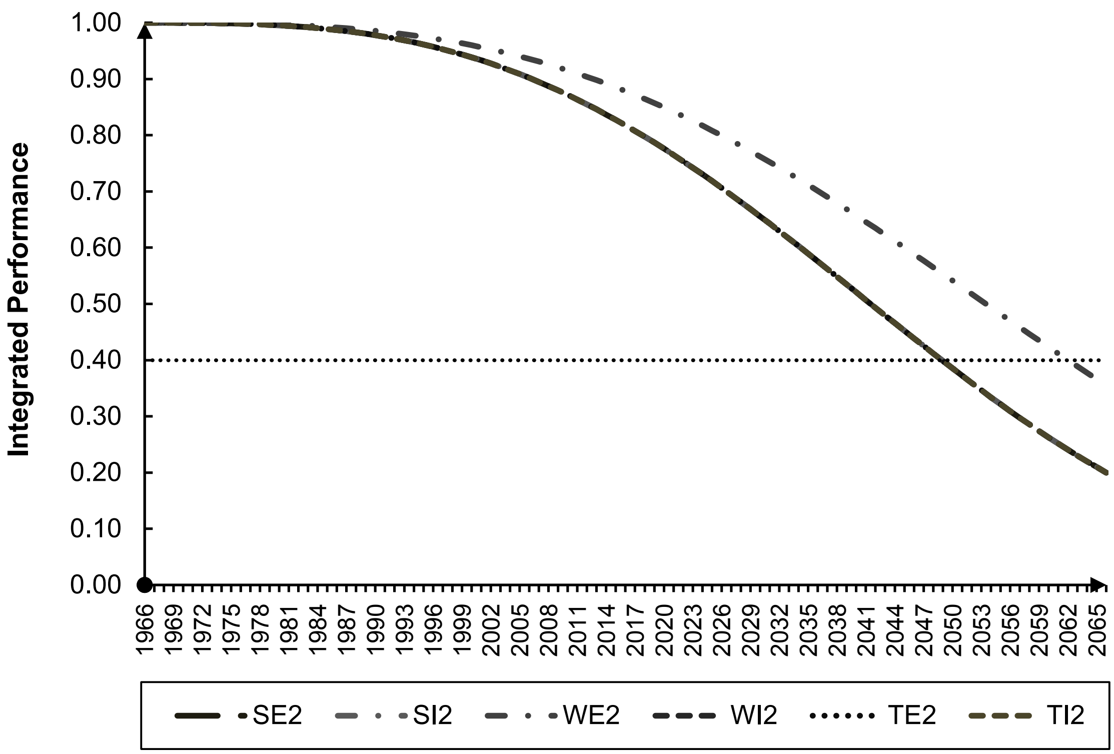

Figure C.3 STA1 2nd Floor Components' Performance Curves

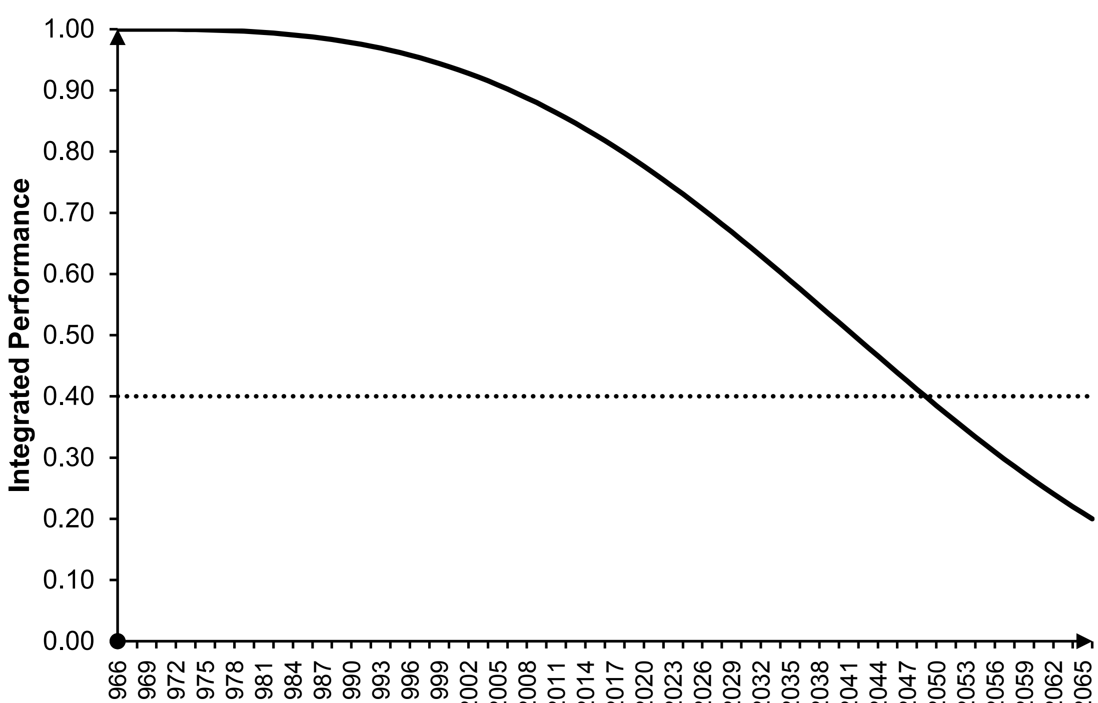

Figure C.4 STA2 Components' Performance Curves

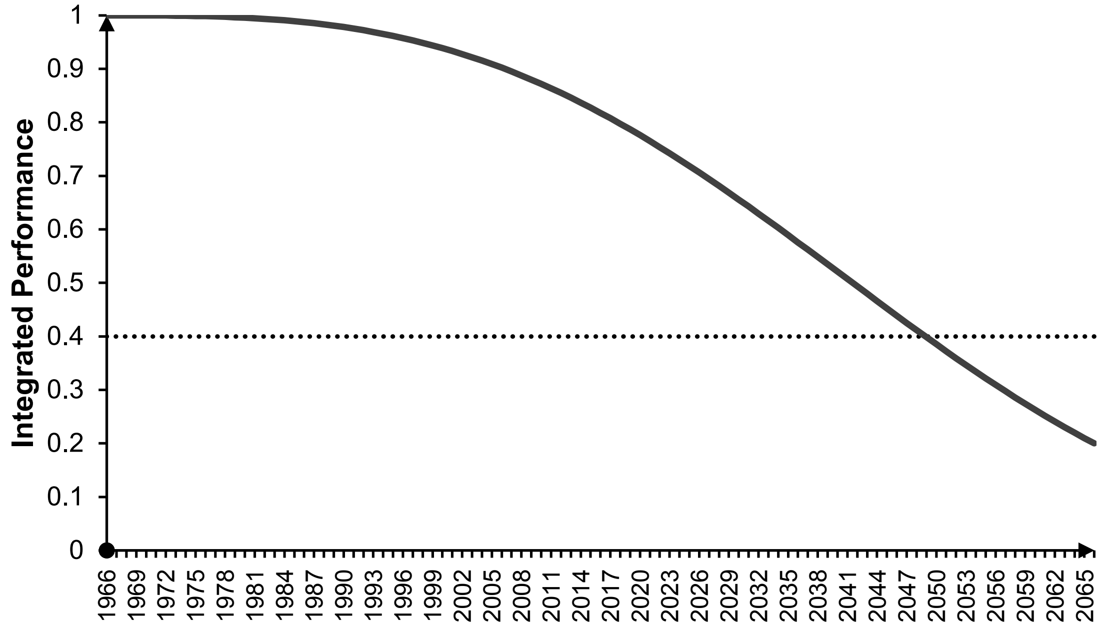

Figure C.5 STA3 Components' Performance Curves

Components: SE0, SI0, WI0, TE0, TI0, TE1, TI1, SI2, WE2, TE2, TI2.

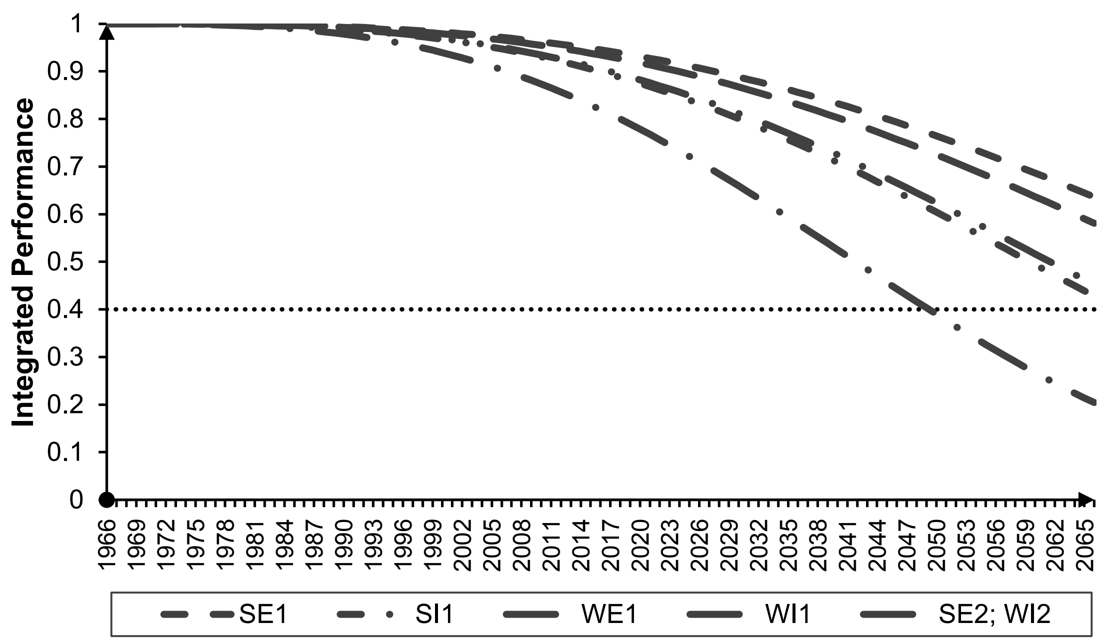

Figure C.6 STA3 Components' Performance Curves

Components: SE1, SI1, WE1, WI1, SE2, WI2.

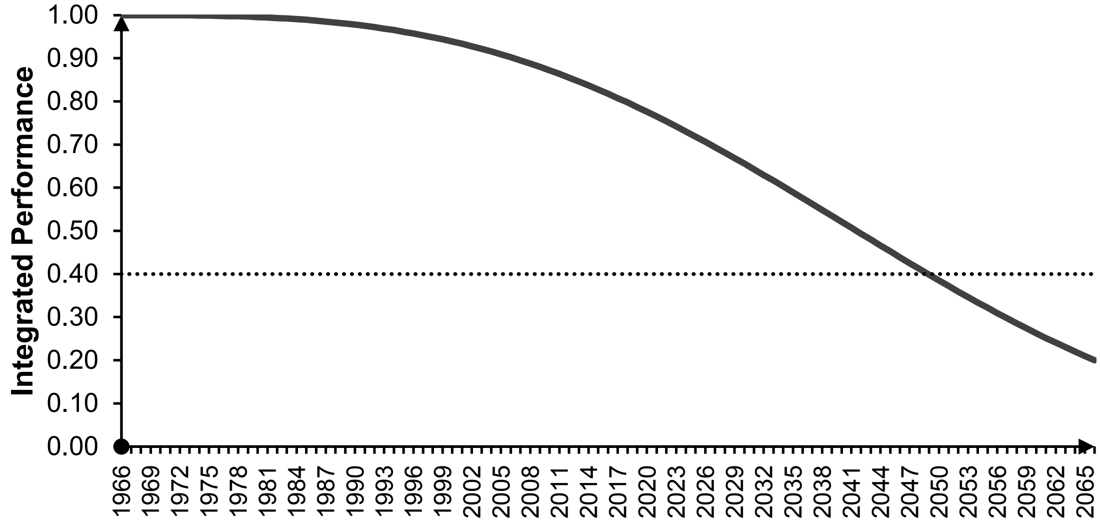

Figure C.7 STA4 Components' Performance Curves

Components: SI0, TE0, TI0, SI1, TE1, WE2, WI2, TI2, TI3, SI4, WI4, TE4, TI4.

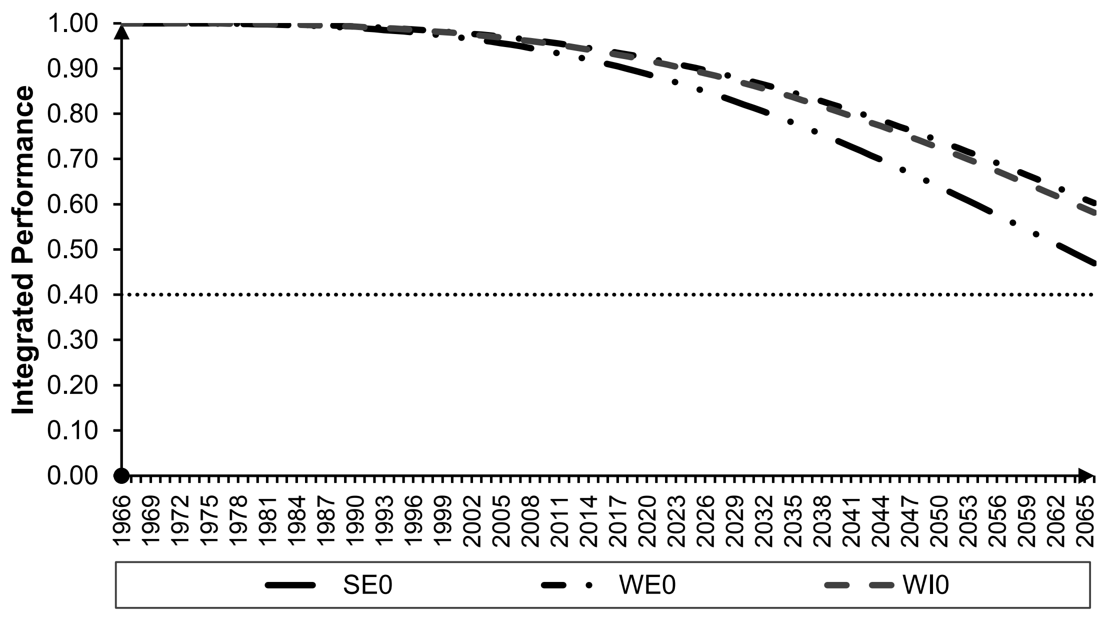

Figure C.8 STA4 Components' Performance Curves

Components: SE0, WE0, WI0.

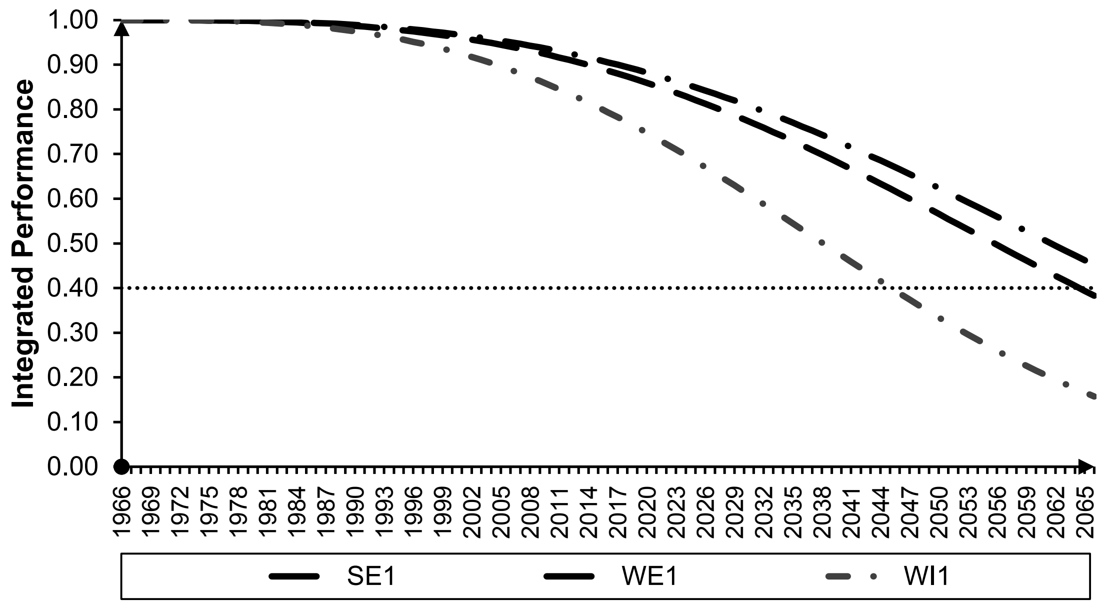

Figure C.9 STA4 Components' Performance Curves

Components: SE1, WE1, WI1.

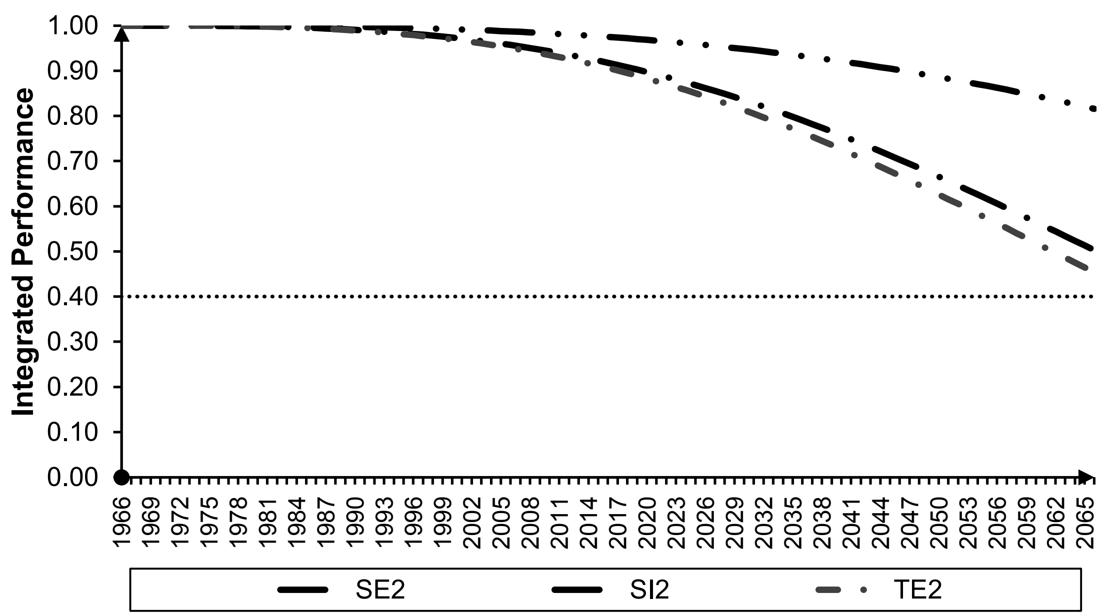

Figure C.10 STA4 Components' Performance Curves

Components: SE2, SI2, TE2.

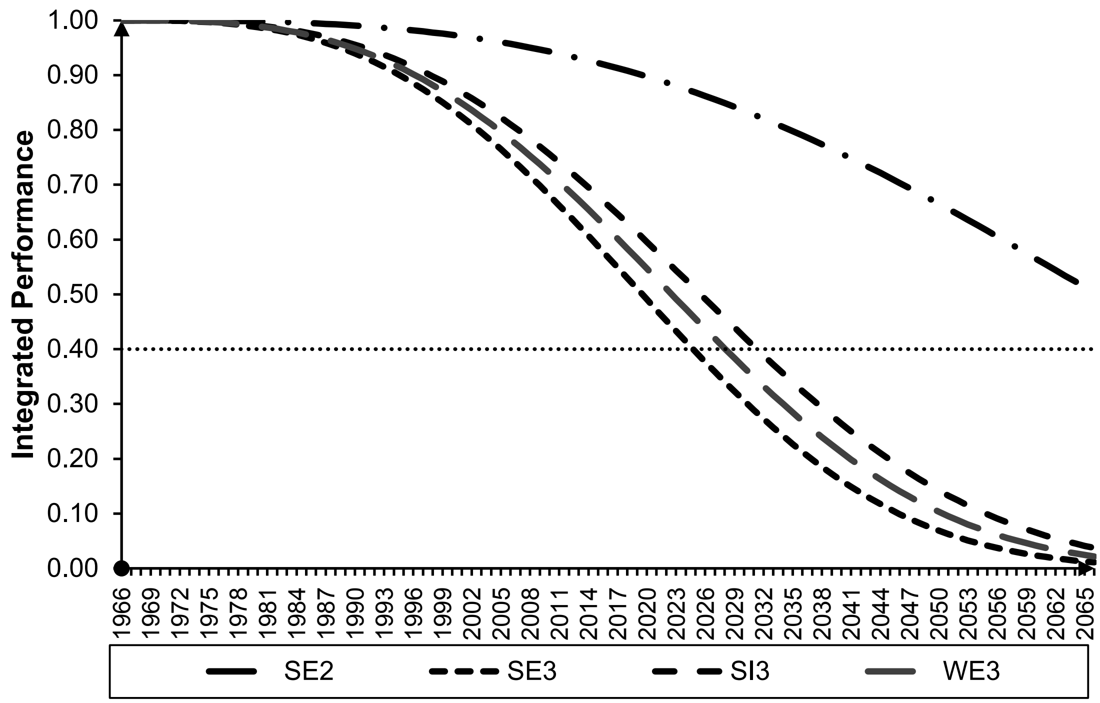

Figure C.11 STA4 Components' Performance Curves

Components: SE3, SI3, WE3, TE3.

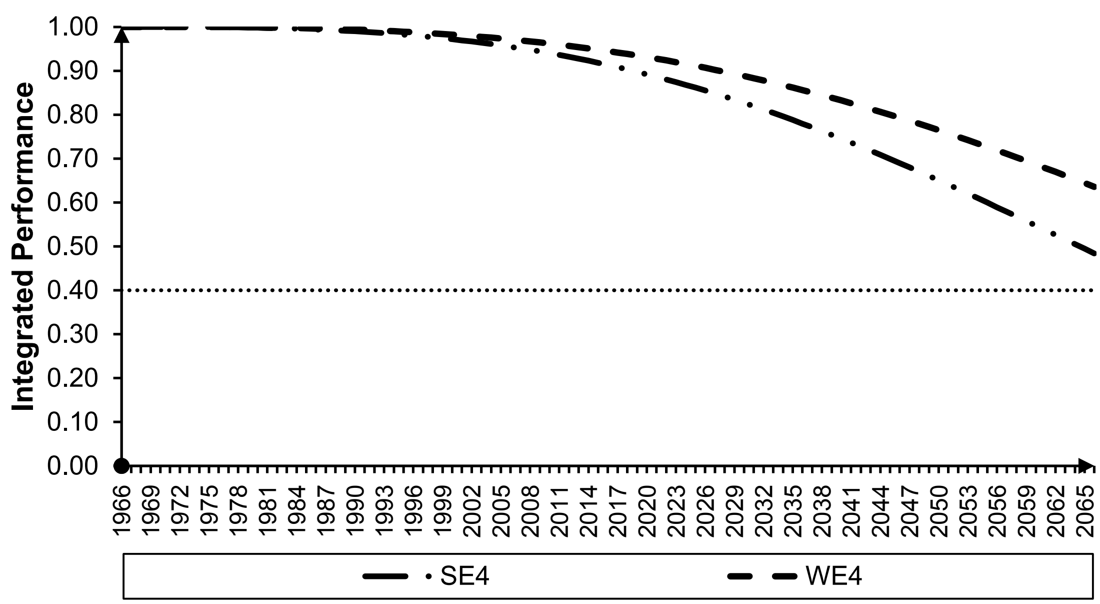

Figure C.12 STA4 Components' Performance Curves

Components: SE4, WE4.

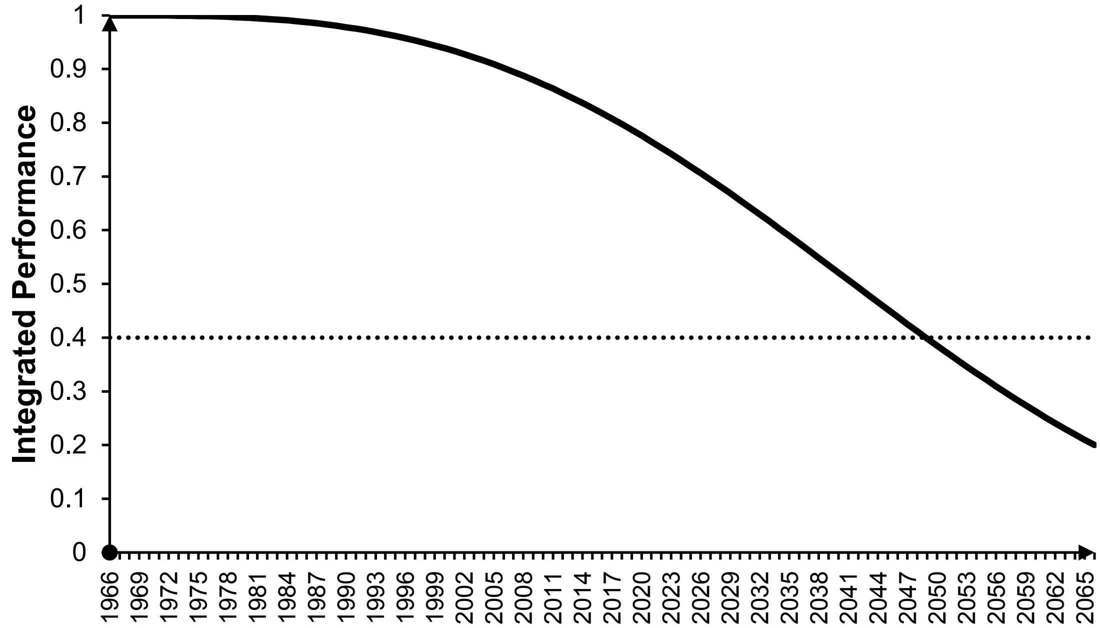

Figure C.13 STA5 Components' Performance Curves

Components: SE0, SI0, WE0, WI0, TE0, TI0, SI1, WI1, TE1, SI2, WE2, WI2, TE2, TI2, SE3, SI3, WE3, TE3, TI3.

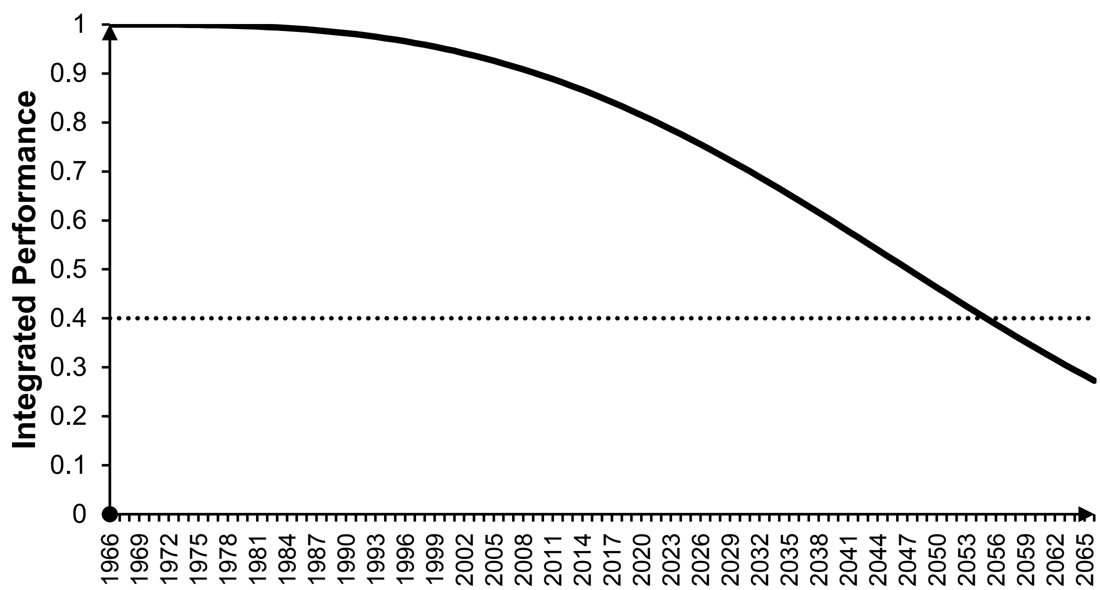

Figure C.14 STA5 Components' Performance Curves

Components: SE1, WE1, SE2, WI3.

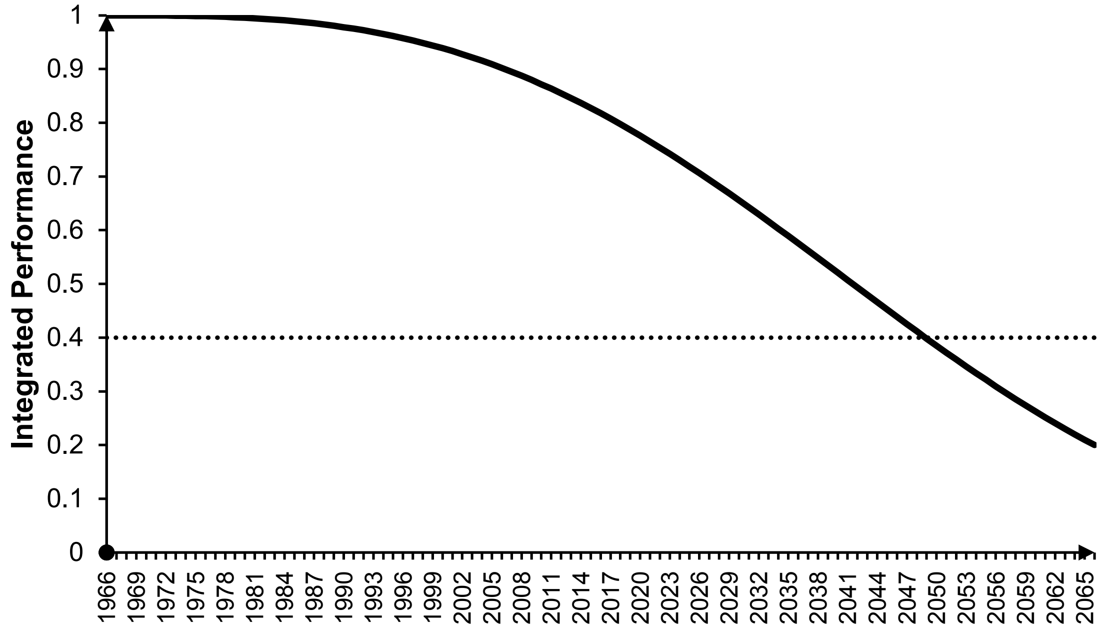

Figure C.15 STA6 Components' Performance Curves

Components: SE0, SI0, WE0, WI0, TE0, TI0, SE1, TI1, SE2, TE2, TI2.

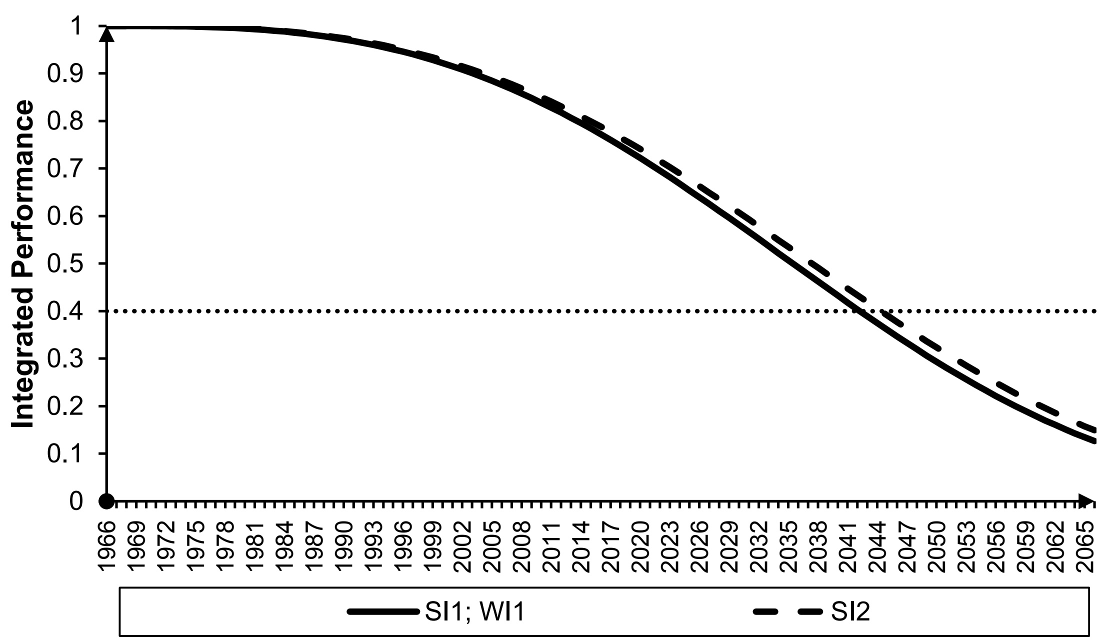

Figure C.16 STA6 Components' Performance Curves

Components: SI1, WI1, SI2.

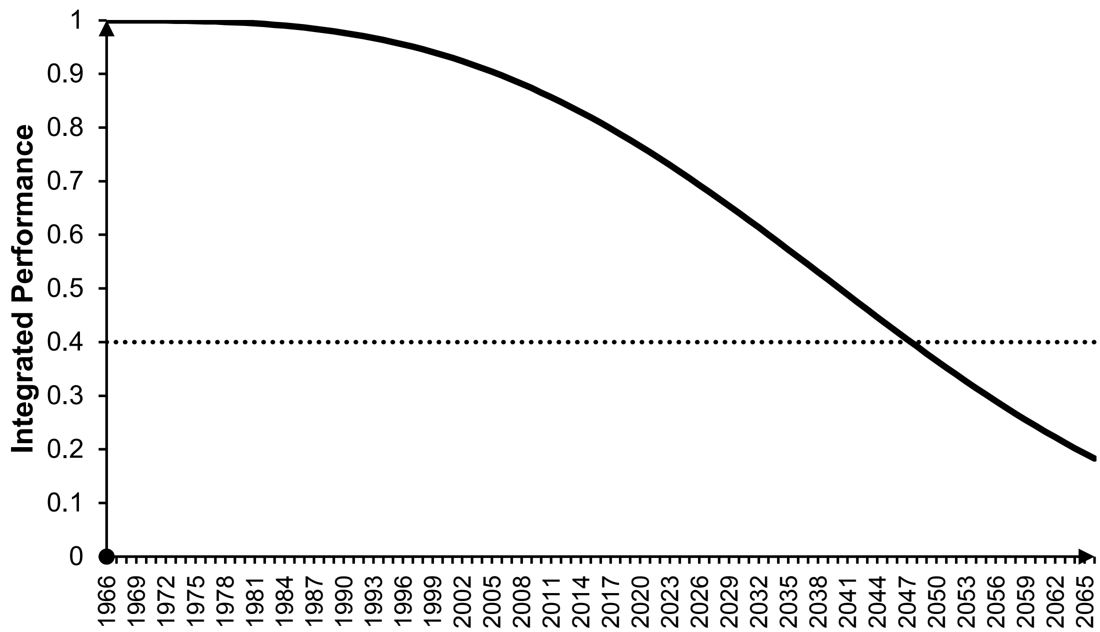

Figure C.17 STA6 Components' Performance Curves

Components: TE1, WE2, WI2.

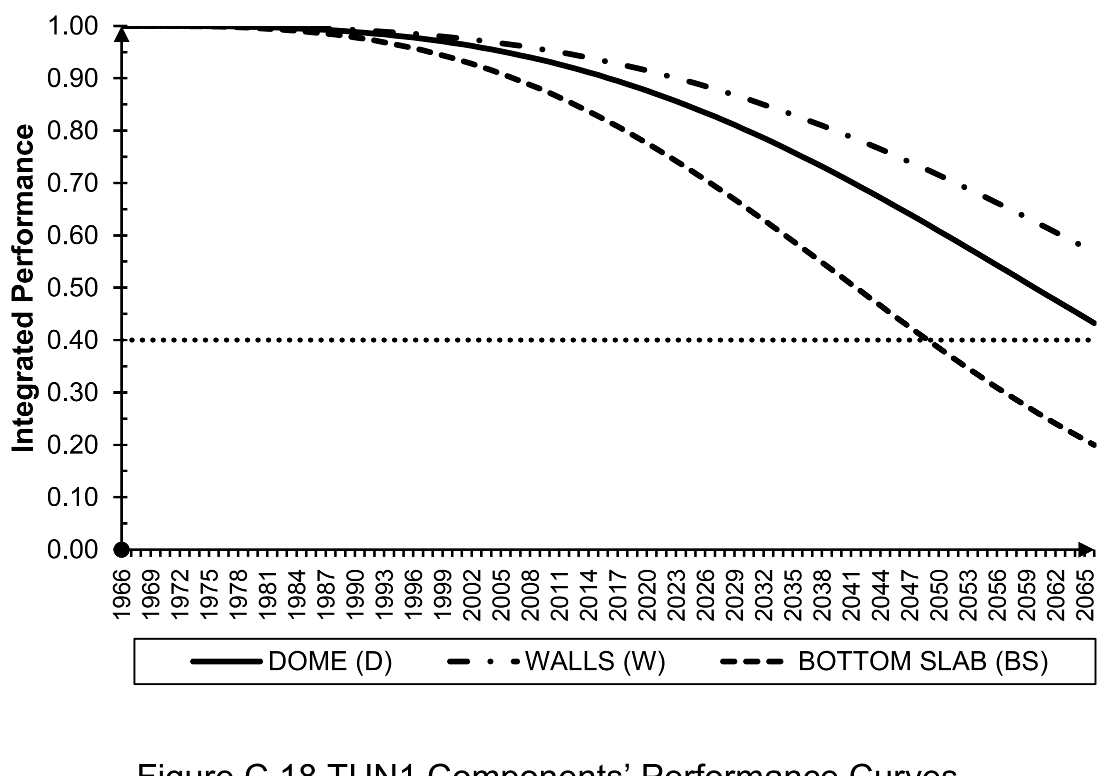

Figure C.18 TUN1 Components' Performance Curves

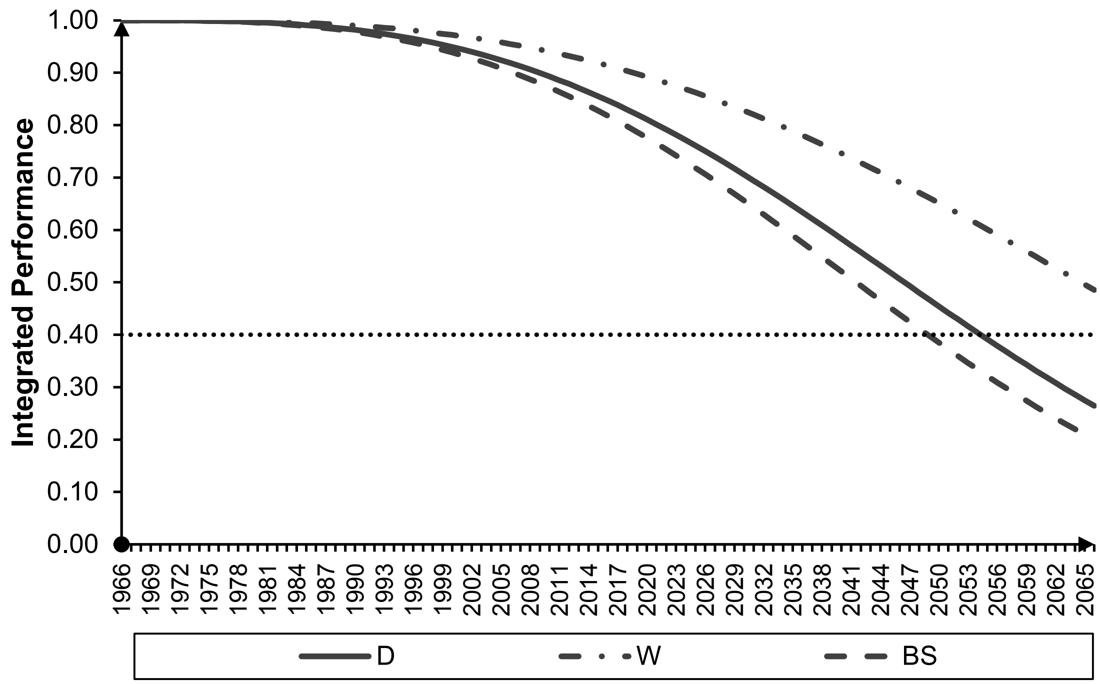

Figure C.19 TUN2 Components' Performance Curves

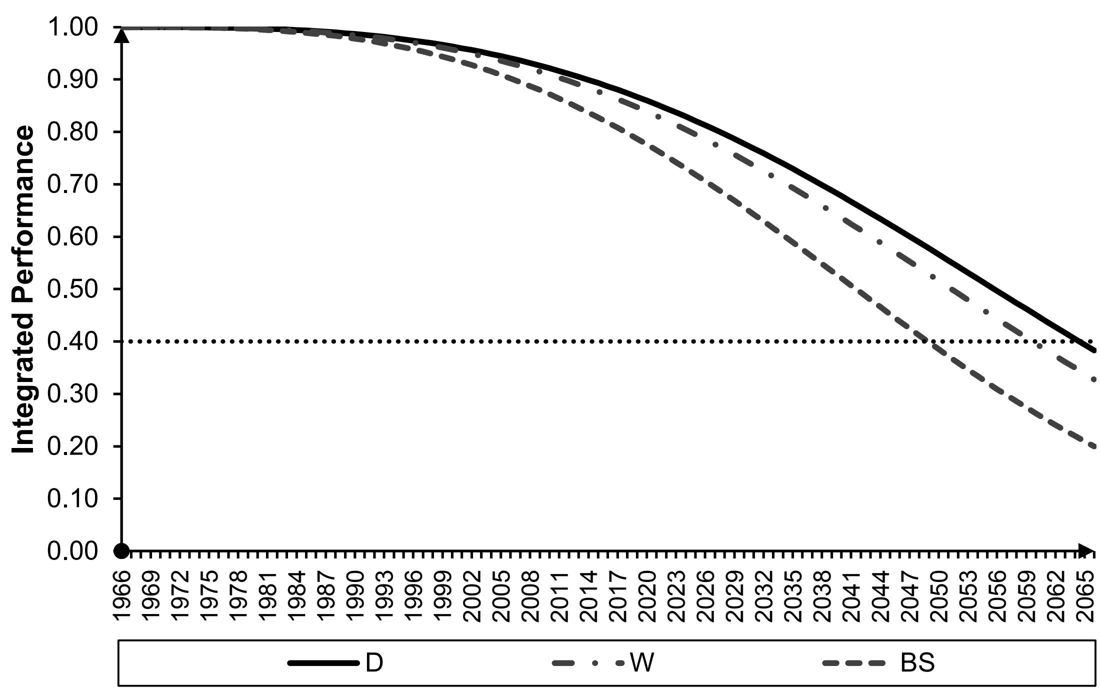

Figure C.20 TUN3 Components' Performance Curves

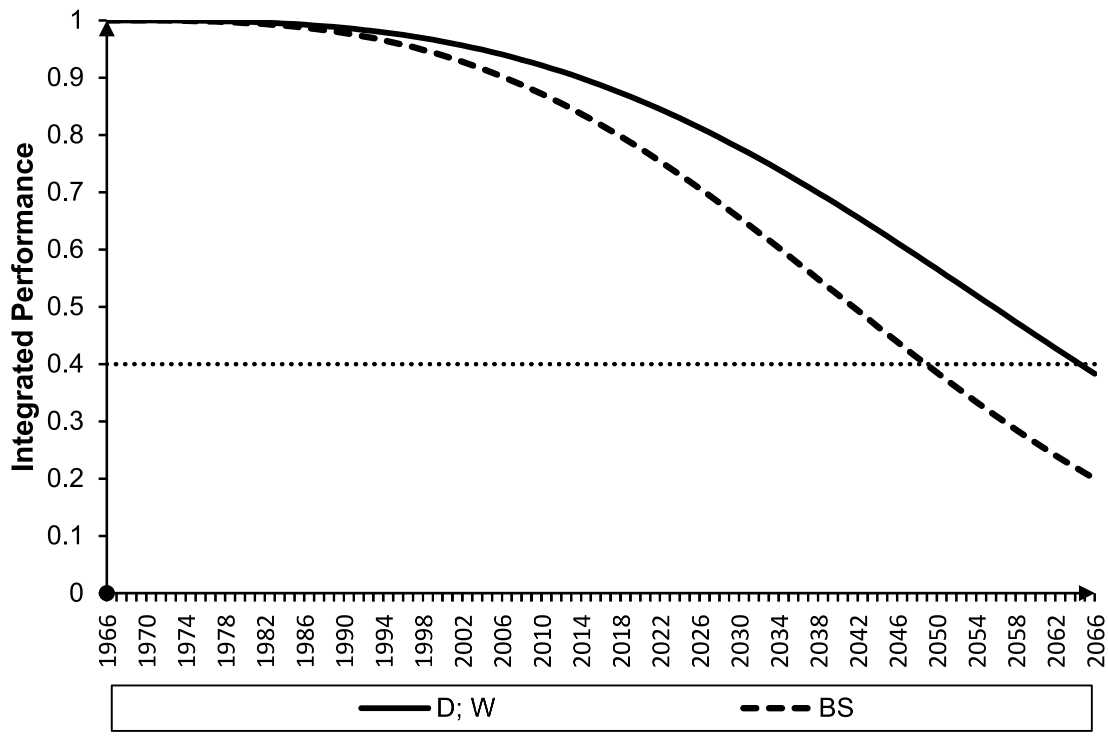

Figure C.21 TUN4 Components' Performance Curves

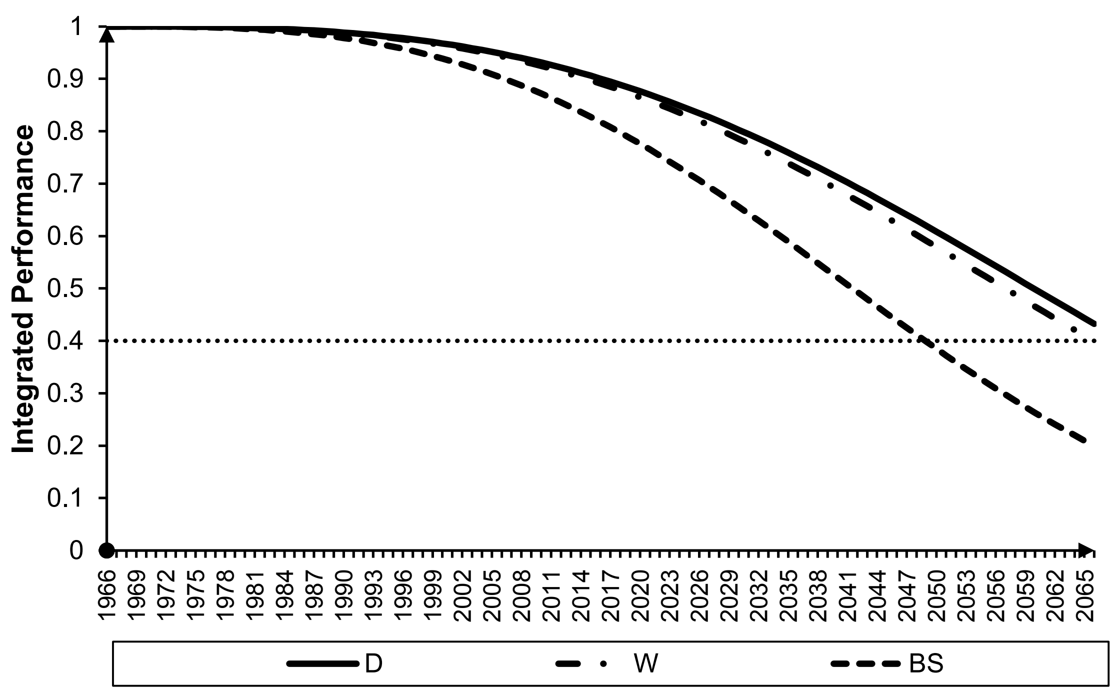

Figure C.22 TUN5 Components' Performance Curves

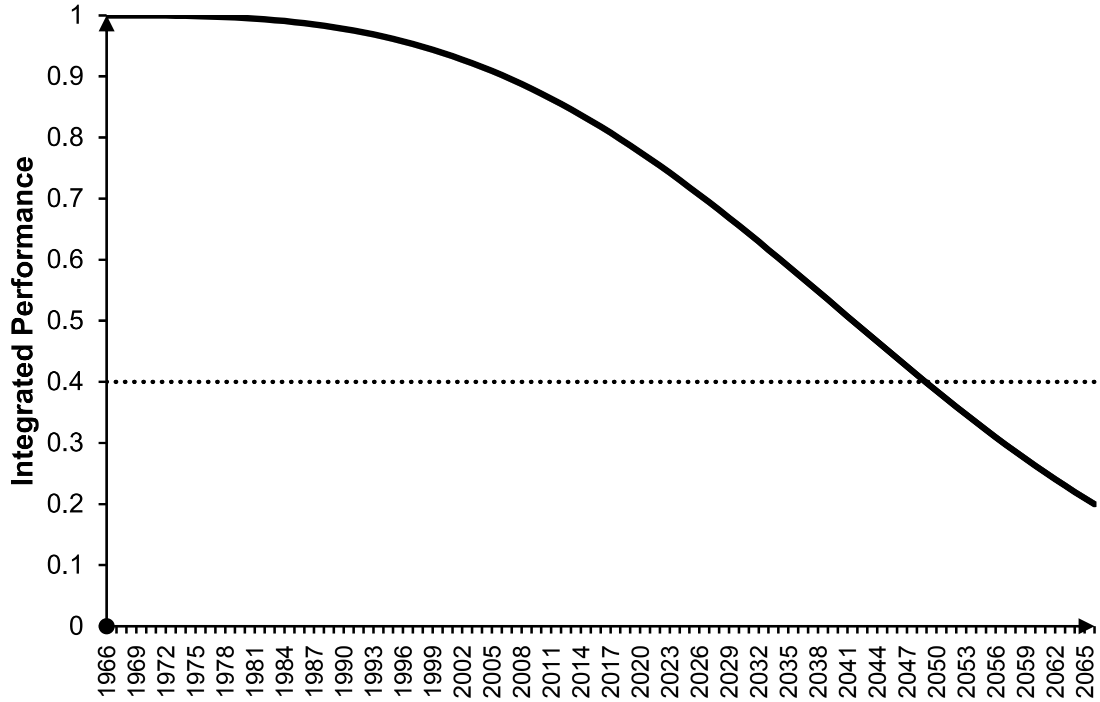

Figure C.23 TUN6 Components' Performance Curves

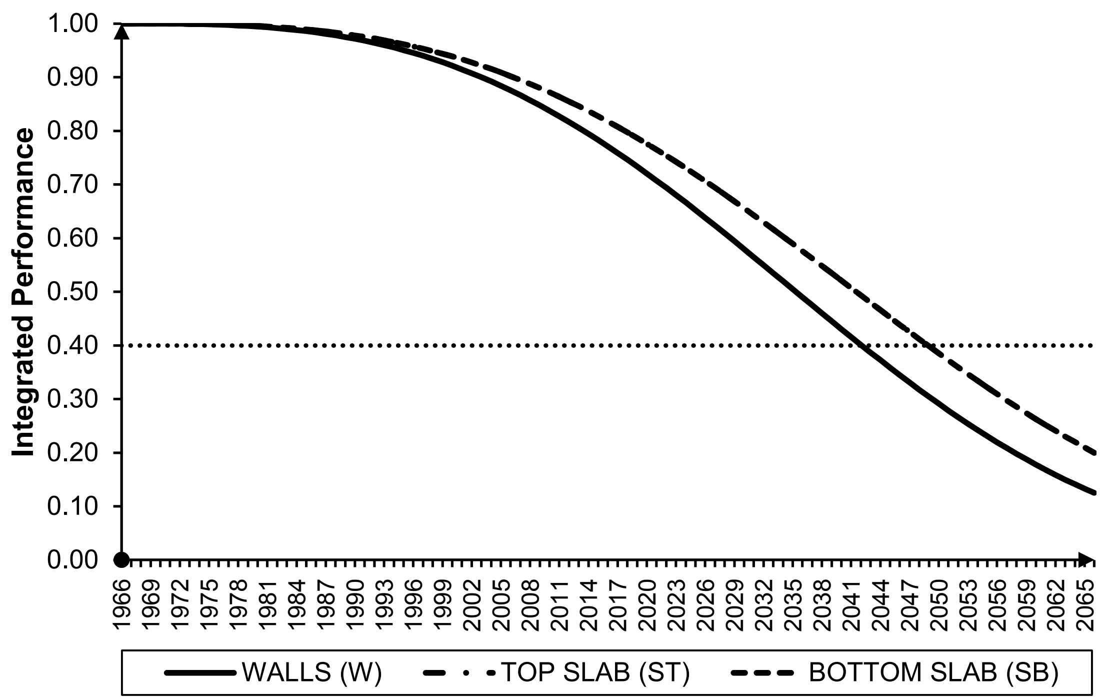

Figure C.24 AS1 Components' Performance Curves

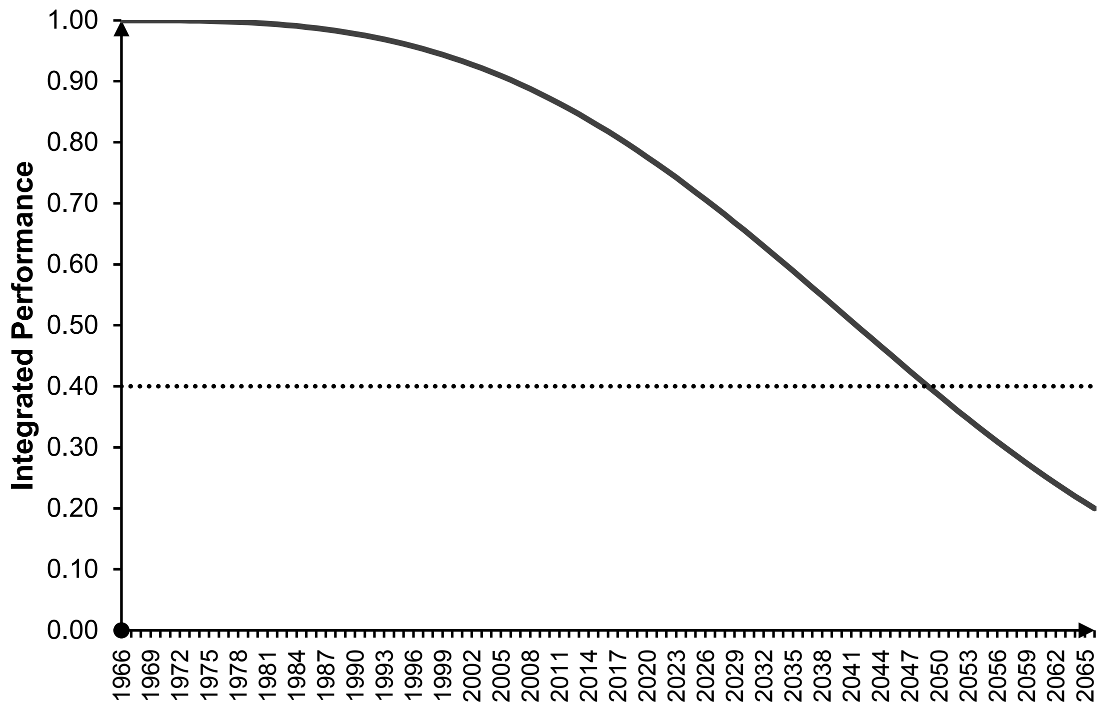

Figure C.25 AS2, AS3, AS5 and AS6 Components' Performance Curves

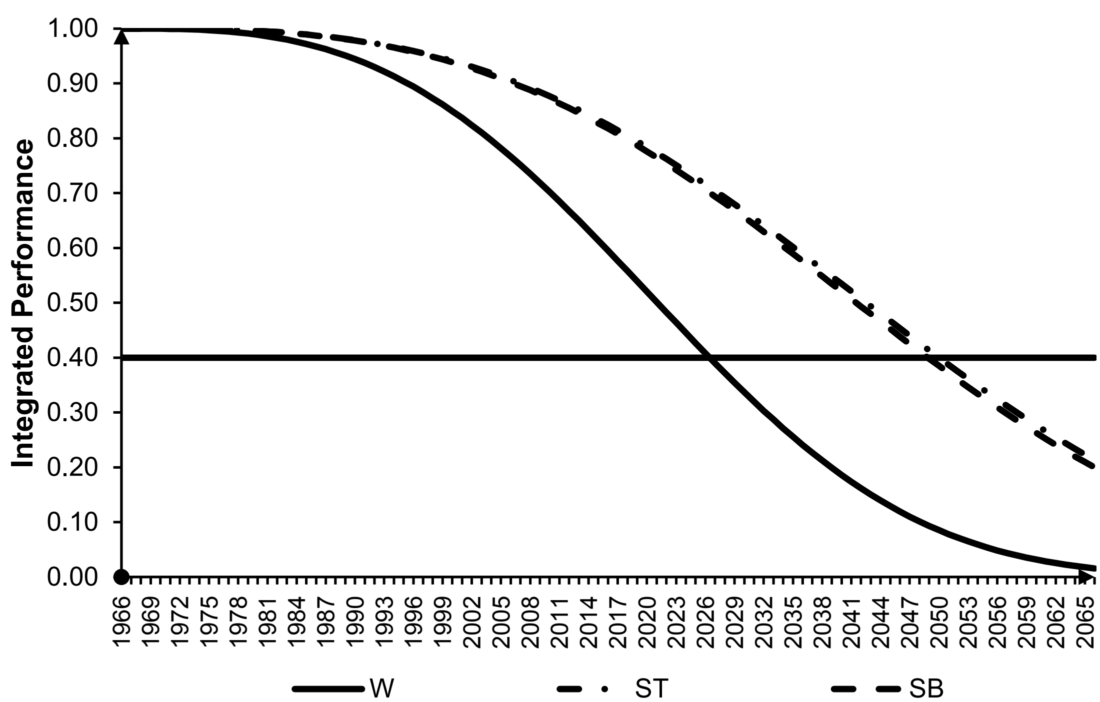

Figure C.26 AS4 Components' Performance Curves

APPENDIX D

SUPER MODEL IMPLEMENTATION TO STM

Systems' Integrated Performance Curves

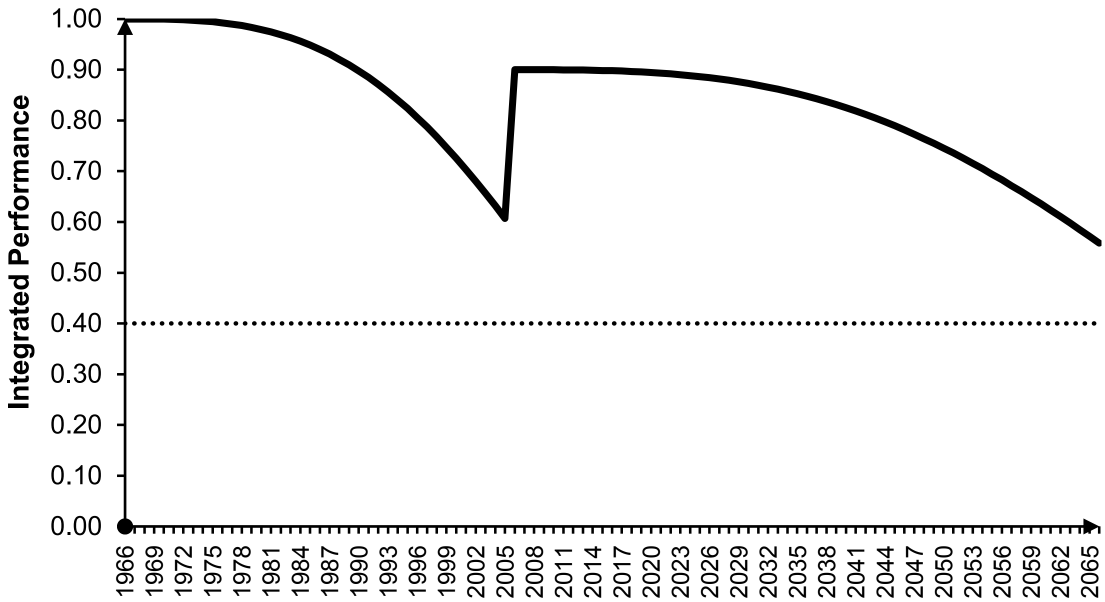

Figure D.1 STA1 Performance Curve

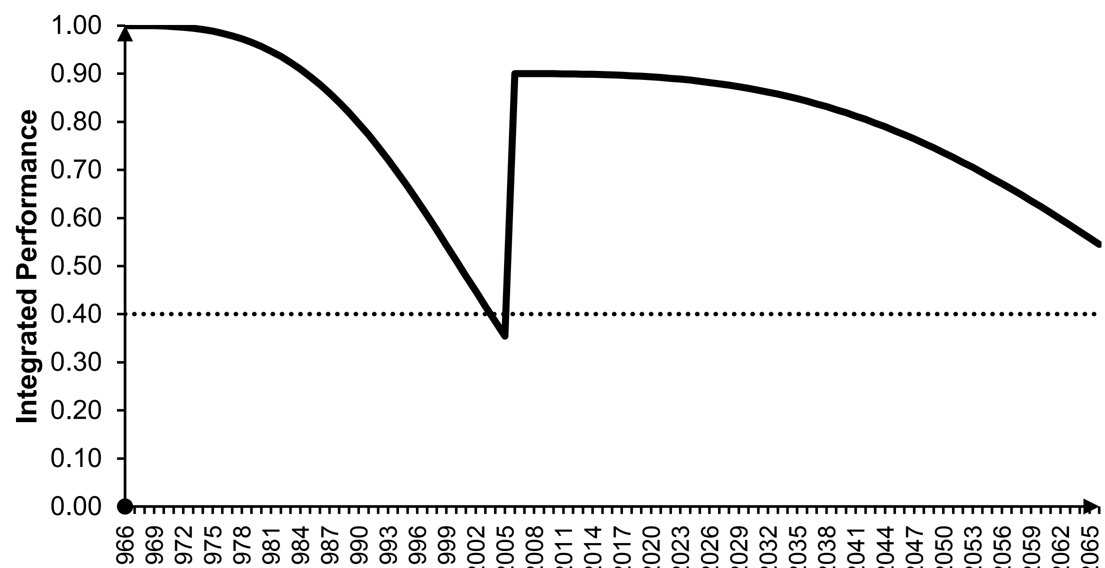

Figure D.2 STA2 Performance Curve

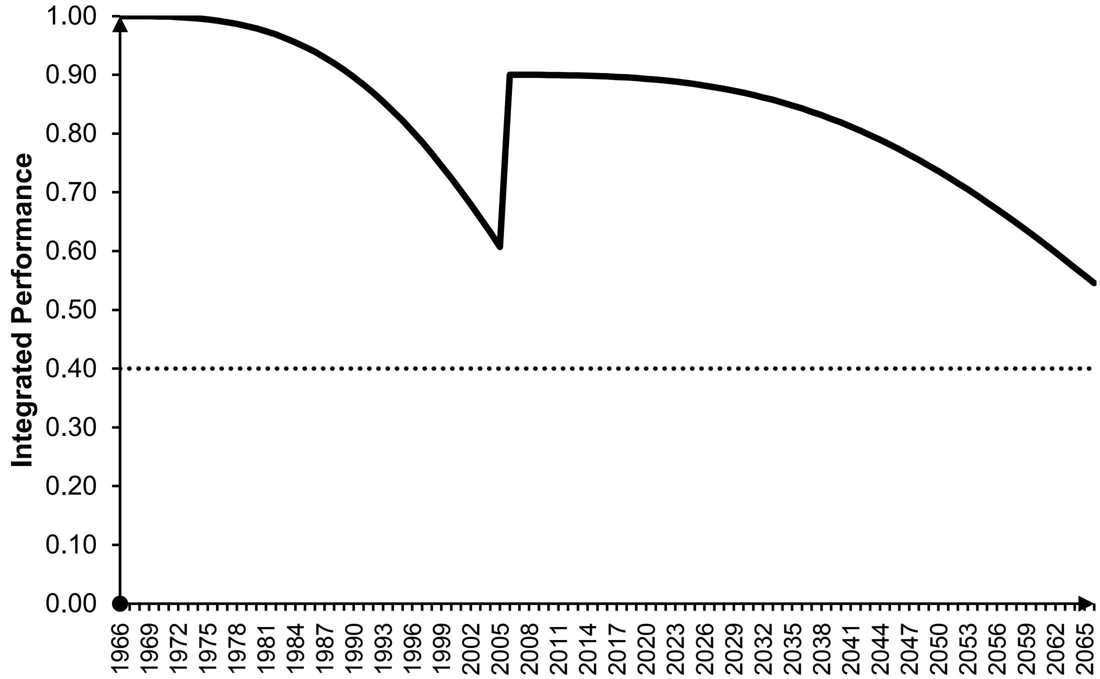

Figure D.3 STA3 Performance Curve

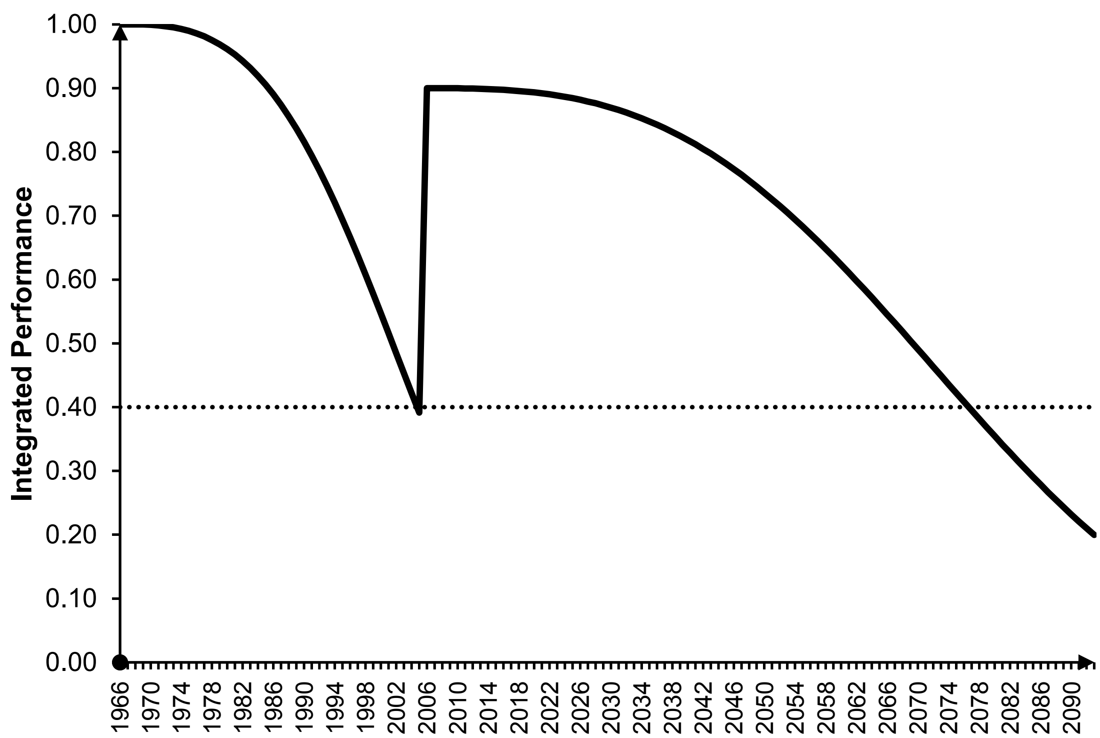

Figure D.4 STA4 Performance Curve

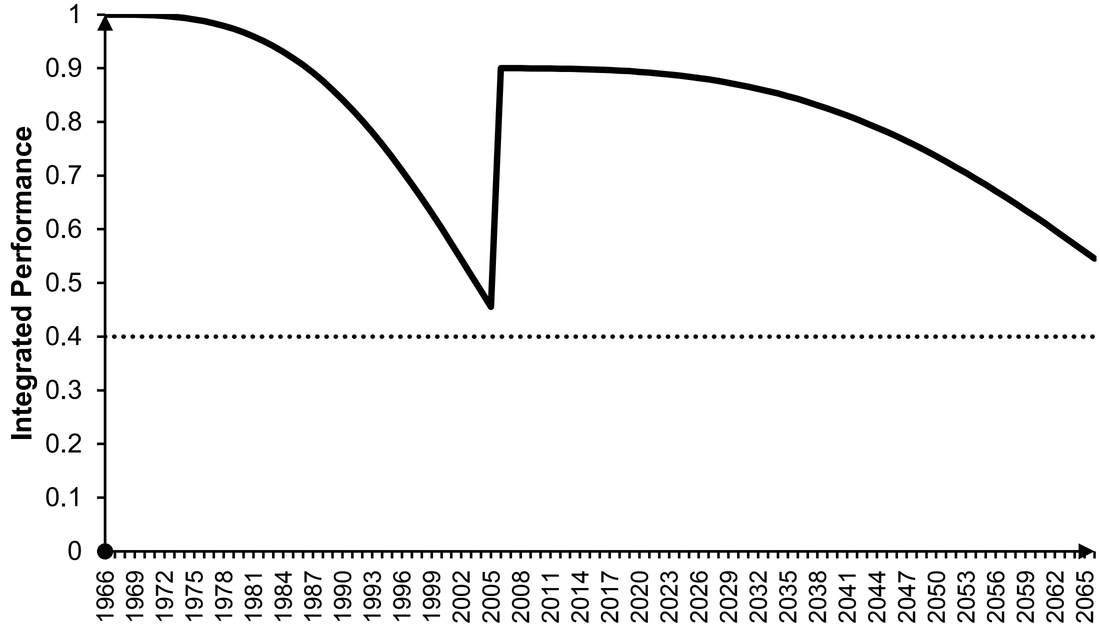

Figure D.5 STA5 Performance Curve

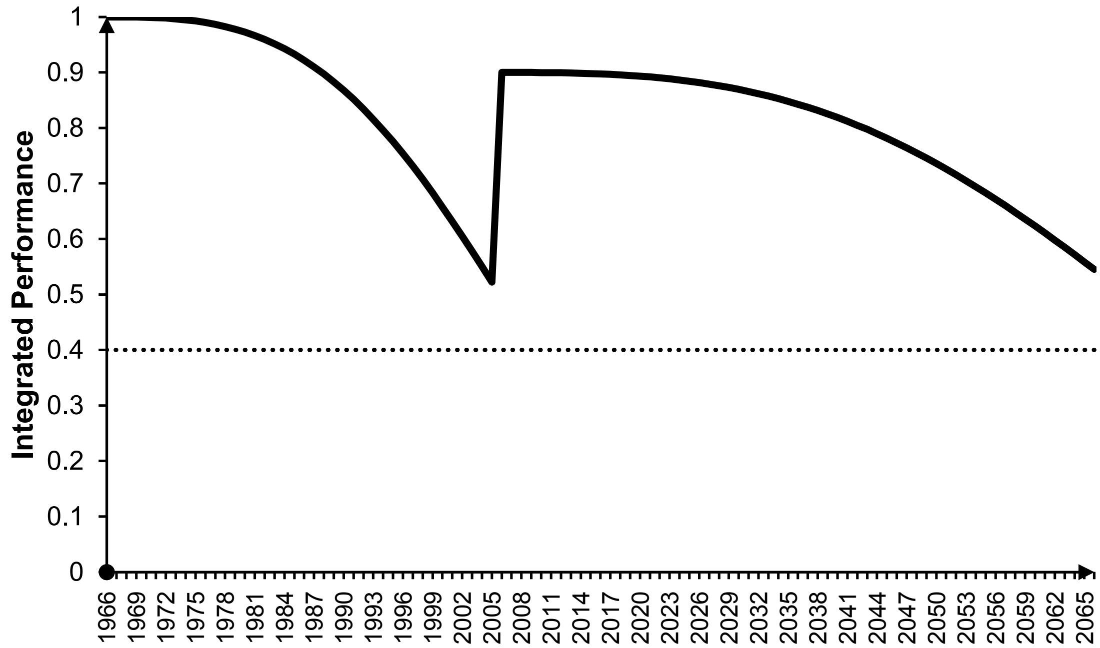

Figure D.6 STA6 Performance Curve

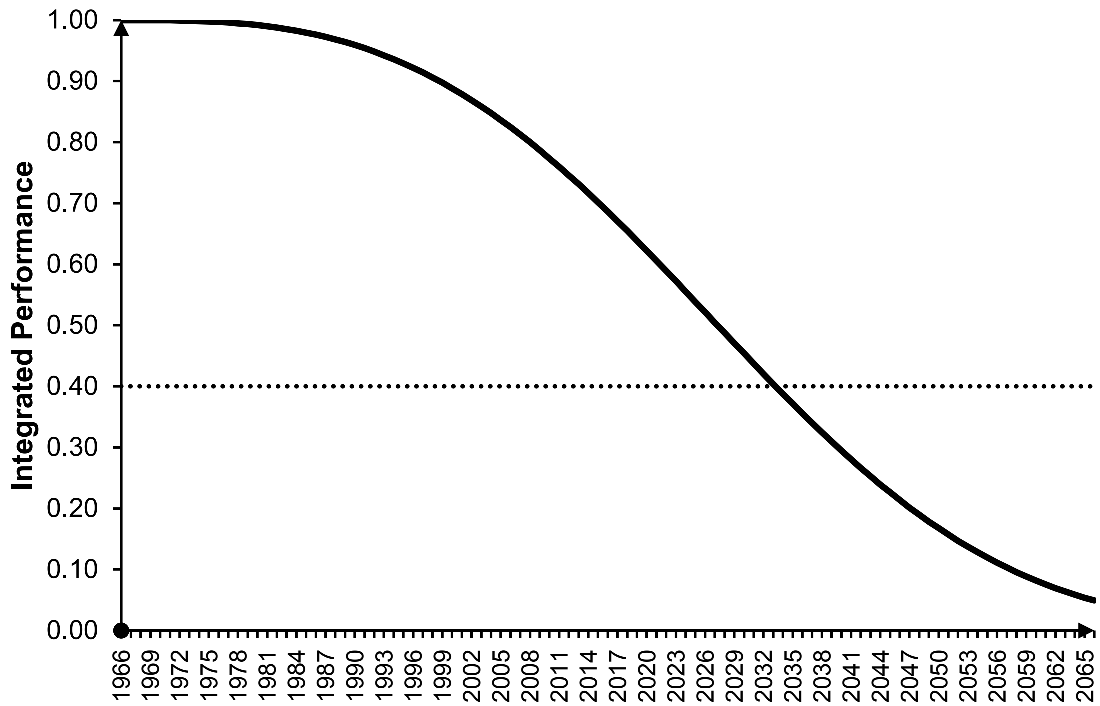

Figure D.7 TUN1 Performance Curve

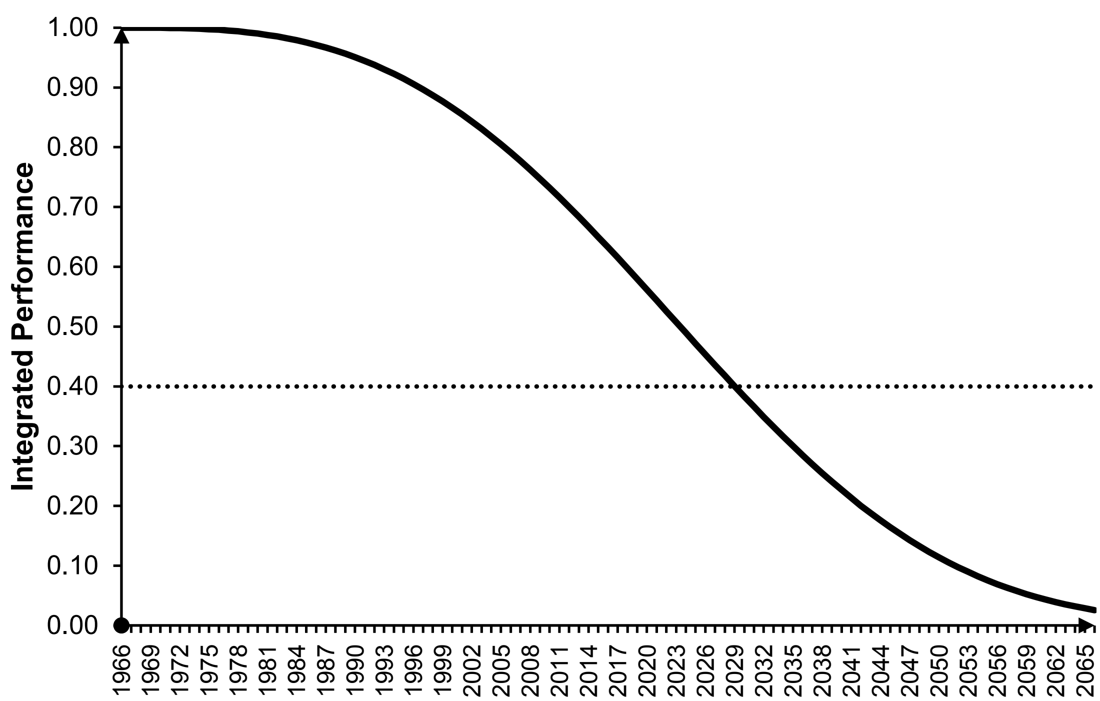

Figure D.8 TUN2 Performance Curve

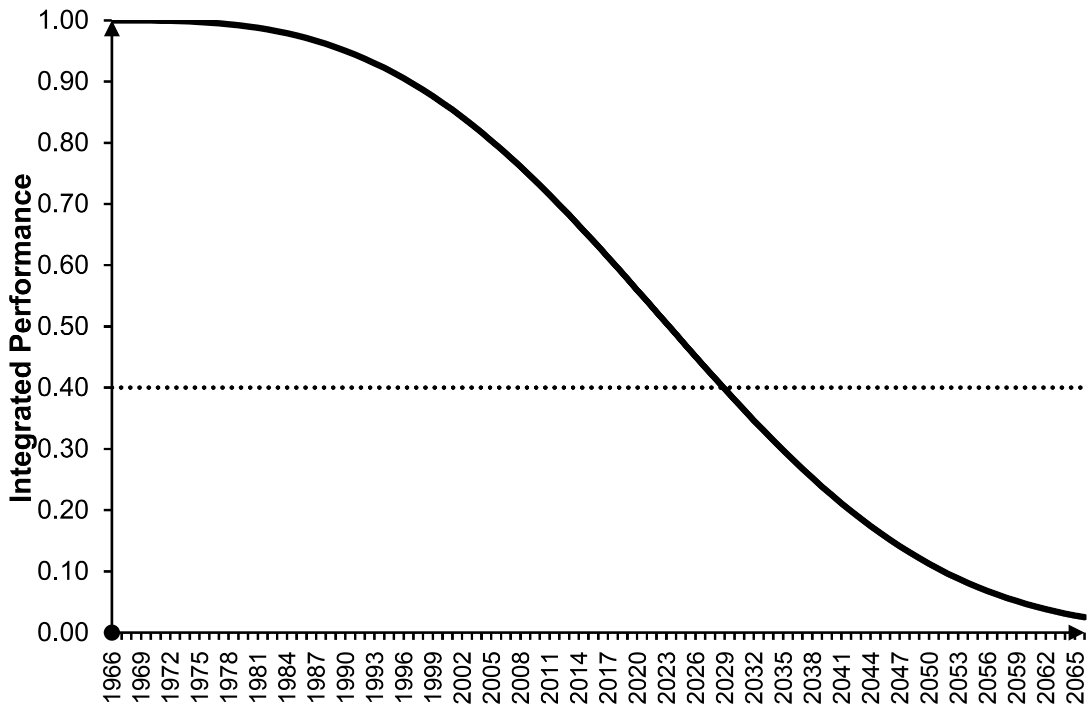

Figure D.9 TUN3 Performance Curve

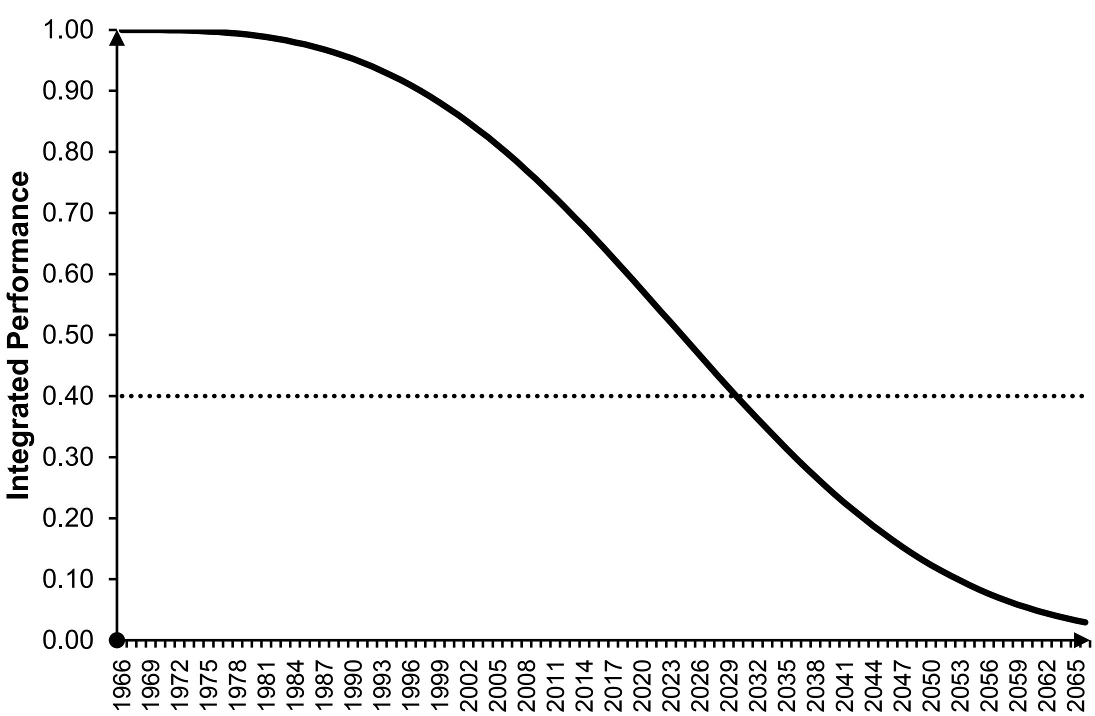

Figure D.10 TUN4 Performance Curve

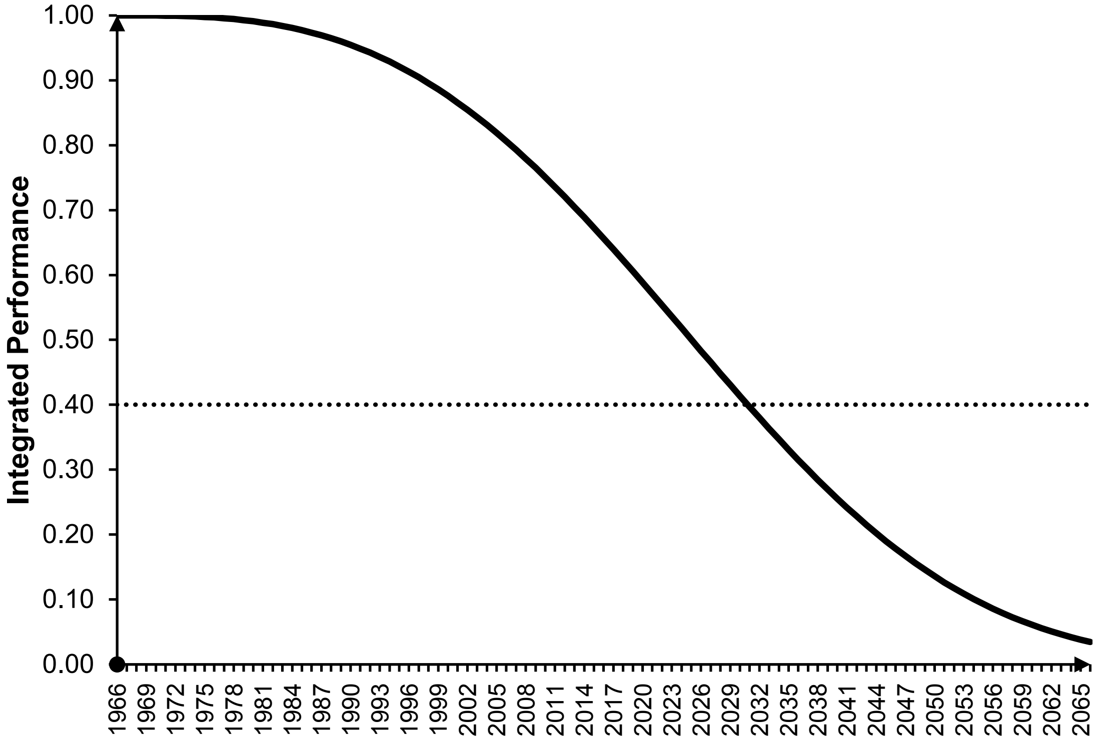

Figure D.11 TUN5 Performance Curve

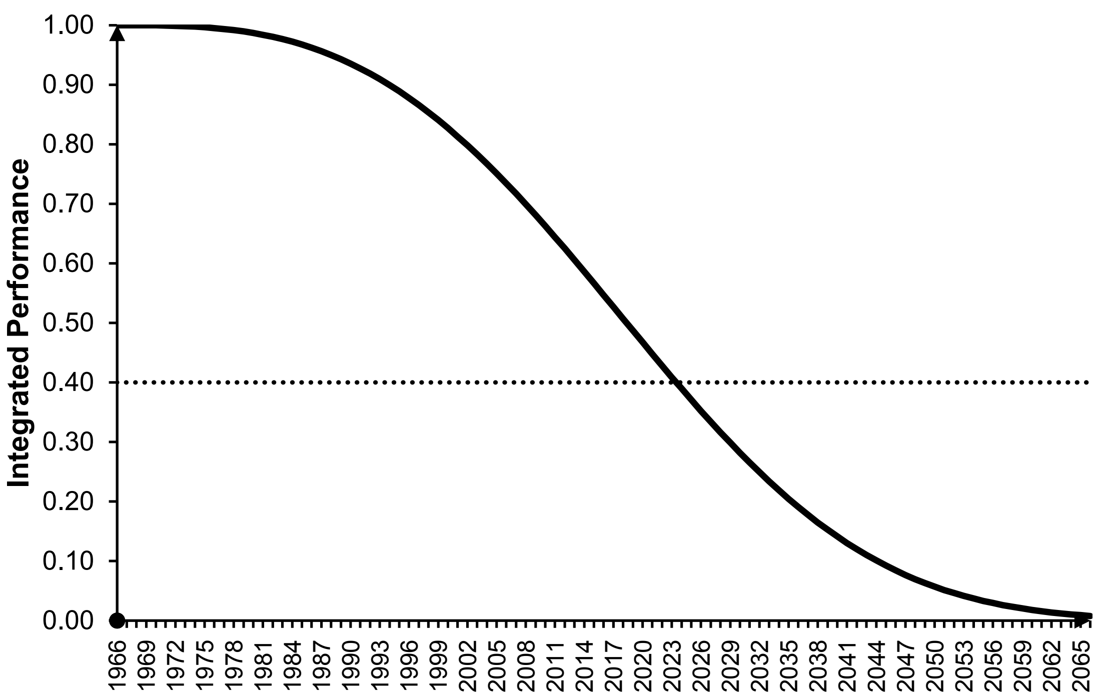

Figure D.12 TUN6 Performance Curve

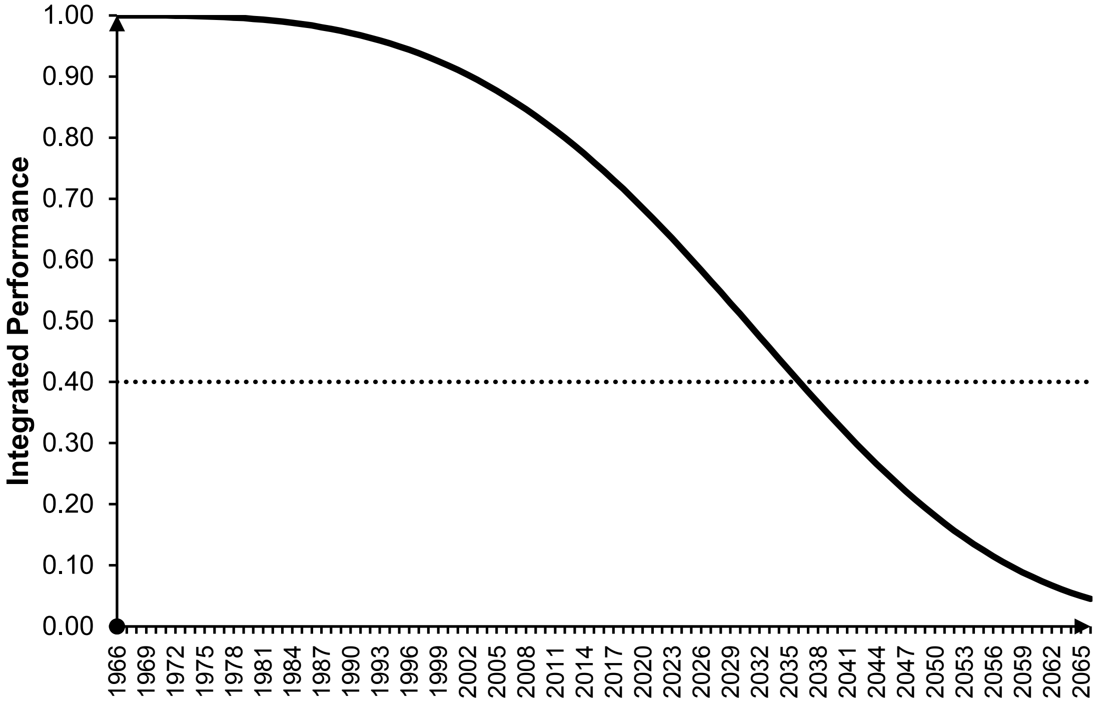

Figure D.13 AS1 Performance Curve

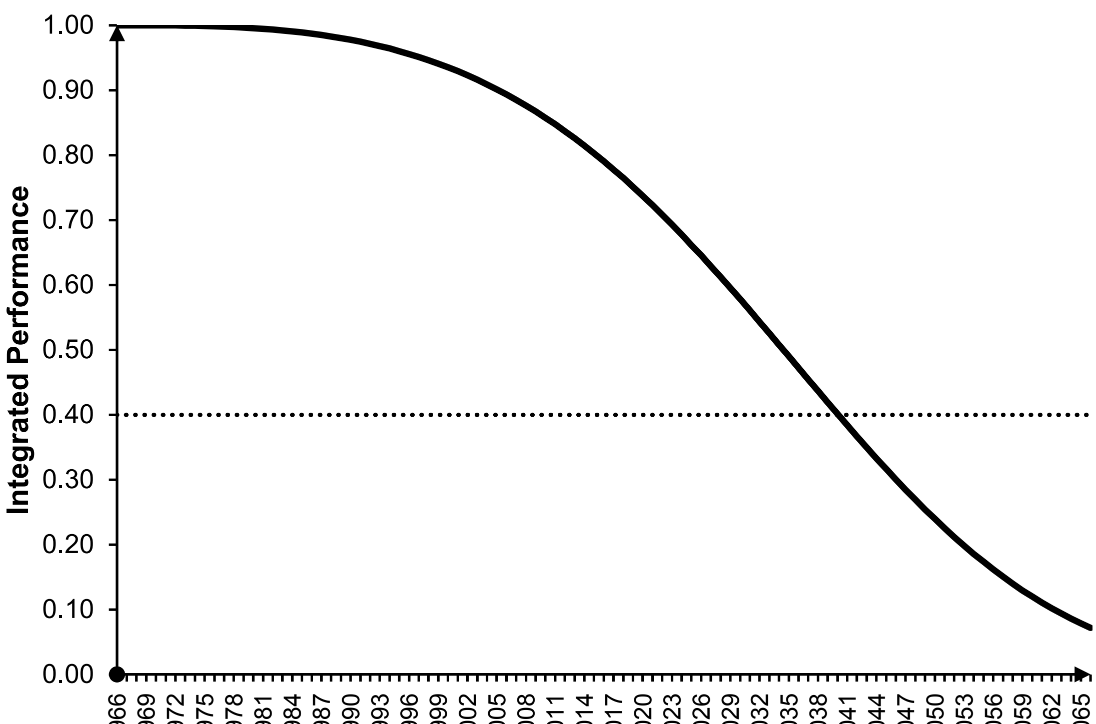

Figure D.14 AS2, AS3, AS5 and AS6 Performance Curve

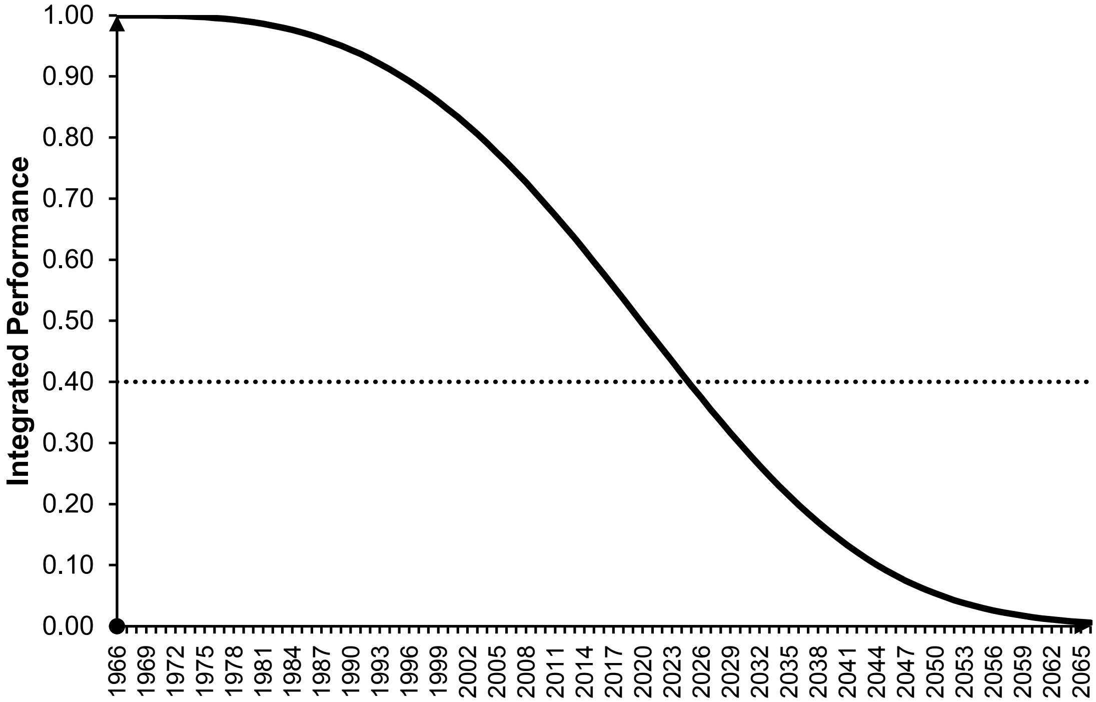

Figure D.15 AS4 Performance Curve