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AN ASSESSMENT MODEL FOR STRUCTURAL PERFORMANCE OF SUBWAY SYSTEMS

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Abstract: The transit federal administration estimated in 2009 that 15.8 billion USD is needed annually to maintain and 21.6 billion USD in order to improve the US transit network to reach satisfactory conditions. This paper focuses on a new developed model that assesses the structural performance assessment of the subway systems' elements. This model (i) identifies the hierarchy for different elements, (ii) assesses the physical condition and functional performance, and (iii) develops an integrated performance index. The model uses the analytic hierarchy process and multi-attribute utility theory mathematical tools in order to evaluate the performance factors weights and indices respectively. Data are collected from the Société de Transport de Montréal inspection reports and through questionnaires. The developed model is implemented to several systems within the STM subway network. Results show that some elements have deteriorated by 5% in 40 years while others by 5% in 14 years. This research is relevant to industry practitioners and researchers since it develops a structural performance assessment model for subway systems.

Keywords: Structures & Structural Stability, Analytical techniques, Assessment, Defects, Deterioration, Infrastructure, Mathematical models, Sensitivity analysis, Structural failures, Transportation networks

1. INTRODUCTION

Civil public transportation infrastructure is crucial for economic growth and prosperity. 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. 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. Also, according to the *Canadian urban transit association* (CUTA), the transit infrastructure needs are reported to total53.5billion Canadian dollars in 2010in Canada (CUTA, 2010). Thus, subway networks are deteriorating in time due to a continuous increase in loading frequency and severity, and due to harsh environmental conditions. For instance, STM estimated an amount of 5.1 billion

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Canadian dollars for its subway system infrastructure' maintenance for the next ten years, starting 2010. With this rapid deterioration of the subway system infrastructure and the 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. Several major attempts were done in USA mainly that develop plans for asset management, such as the Transit Economic Requirements Model (TERM) of FTA, and the State of Good Repair (SGR) of the Massachusetts Bay Transit Authority (MBTA), and confirmed by the 'Moving Ahead for Progress in the 21st century' (MAP21) in 2012. Still, these attempts do not solve the problem of the structural performance current condition detailed assessment and the future performance prediction of the subway network. The major problems facing the subway authorities are summarized as follows:

(i) Fast structural deterioration of existing subway networks;
(ii) Limited scope of existing subway structural deterioration models;
(iii) Non existing subway structural performance predication models;
(iv) Lack of integration of condition and safety in a unique structural performance model.

This research paper focuses on the structural performance assessment of the subway systems elements solely. The proposed model has the following objectives:

(i) Identify and study the structural performance factors and their associated cracks and defects,
(ii) Assess the structural Physical Performance Index (P_P) and the structural Functional Performance Index of (P_F)the elements (in each system), and
(iii) Integrate both physical (condition) and functional (safety) performance indices into one integrated structural performance index (P_I).

2. BACKGROUND

2.1 The Existing Subway Performance Models

Although subway networks in major cities worldwide are aging, a unified performance model has not been developed. However, few studies have started in this field.

The first major research on subways was done by Abu-Mallouh, in 1999 who developed a 'Model for Station Rehabilitation Planning' (MSRP) for the metropolitan transit authority of New York city transit (MTA NYCT). The MSRP is mainly a subway station 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 (such as 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. The MSRP is a model for ranking the stations and not for evaluating a condition or assessing deterioration of the station. It cannot be considered a structural assessment tool, and also it looks at the station as a whole, without specifying the deteriorated elements.

In 2006, another subway station 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 is a diagnostic model that gives a general idea of the condition of the station as a whole. It does not focus on the structural condition nor specifies which element is problematic. Hence, it is cannot be considered a purely structural condition assessment tool. Moreover, structural safety is not considered in this model at all. Furthermore, the SSDI model is developed for subway stations solely; it does not consider subway tunnels and auxiliary structures.

Hence, the existing subway performance models were both developed for subway stations solely. They also, did not study the structural performance in focus and depth; i.e. considering the different structural durability factors. Furthermore, they did not consider structural safety and physical condition in one performance model.

In 2009, the FTA developed TERM for its transit authorities. TERM is used to assess the current physical condition, and develops future investment needs of the assets. TERM starting point is based on the assessment of the current physical condition, and the choice of either to maintain or improve it. The current condition is assessed using a rated score from 5 (excellent) to 1 (poor). This rated score specifies degrees of wear, decay and defect signs subjectively. Furthermore, TERM uses decay curves as forecasts of the current condition. Finally, TERM utilizes either normal replacement of assets reaching their respective useful life, or a mid-life rehabilitation. TERM project has many limitations and constraints. First, it only considers the physical condition, disregarding the safety performance (abitlity to carry the loads safely) of the elements. Second, the score used in TERM fail to specify a technical, physical and numerical level of deterioration. Third, the decay curves are derived on forecasts of the current condition only, without technically identifying the method of forecast. Finally, the model is based on an assumed useful life that does not change.

In 2010, The MBTA developed the State of Good Repair (SGR) asset management system. Its main purpose was the maintenance and modernization of the current transit system. The SGR starts by the assessment of the current existing condition. Then using a useful life for each asset as an asumption, develops investment plans based on the age of each asset as a percentage of the assumed useful life. The main drawback of the SGR system is the use of the assumed useful life and age of the structure as the sole basis of the future condition prediction. Furthermore, SGR system fails to consider the safety performance as well.

In 2012, the MAP 21 was signed and went in effect in USA. MAP 21 provides grants for the transit authorities' asset management programs, by stressing mainly the SGR and safety. However, although MAP21 requires performance measures for SGR, planning and safety, it leaves the freedom to FTA and transit authorities to define and develop the performance measures based on that definition, either through FTA, or independently. Although, MAP 21 is an important step, however it leaves the technical decision of deterioration forecasting to transit authorities. Furthermore, MAP 21 is specific to the USA, while lot of countries do not have such policies.

It can be concluded that the existing research in the field is very limited and not sufficient because the existing models:

(i) only tackled assessment of subway stations, while very limited research was developed for tunnels and auxiliary structures.

(ii) considered structural performance as part of several criteria and hence did not analyze the structural behaviour in depth.

(iii) were limited to the physical condition in a structure, neglecting the safety and functional behaviour of the entire system.

Thus, there is a crucial need for a new model to close the above-mentioned research gaps inherited in the existing models.

2.2 The Existing Infrastructure Performance Models

The closest infrastructure to subway structures are the bridges. The American Association of State Highway and Transportation (AASHTO) in cooperation with the Federal Highway

Administration (FHA) published the National Cooperative Highway Research Program (NCHRP) report 590 (NCHRP Report 590, 2007) for bridges. The purpose of the report is to present a method within a framework for the optimization of the bridge management systems. The Report 590 goal is the establishment of optimal investment funding. The starting point of the proposed framework is to develop a basis upon which the alternative bridge actions could be evaluated. Hence, the report suggests a set of performance criteria (in order to meet the goal) as follows: 1) Preservation of bridge condition (National Bridge Inventory (NBI) condition rating, health index and sufficiency rating); 2) Traffic safety enhancement (geometric and operating rating); 3) Protection from extreme events (vulnerability ratings for scour, fatigue, earthquake, collision, overload and other human-made hazards); 4) Agency cost minimization (initial cost and life-cycle agency cost); and 5) User cost minimization (life-cycle user cost). The problem is identified in this report as a decision-making one. Weights of the above-mentioned criteria are evaluated using the analytic hierarchy process (AHP), while the criteria scales are evaluated using a single-criterion utility function. Then amalgamation is performed using a weighted additive utility function. This framework was implemented, validated and used in the industry.

2.3 Durability of Concrete

In order to study the structural performance of concrete, research investigate the durability 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 elements*" (Sarja and Vesikari, 1996).

Durability defects in concrete can be classified as both structural cracks and structural defects according to the national research council (NRC) (Mailvaganam *et al.,* 2000), and the technical guide of the 'concrete bridge development group' (CBDG) (CBDG, 2002). 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.The different structural cracks of concrete are: Slump cracks, corrosion cracks, flexural cracks, shear cracks, torsional cracks, and bond cracks. On the other hand, the structural defects are mainly caused by induced moisture movement and chemical attacks. A list of the some typically identifiable structural defects is: crazing, corner cracks, corrosion cracks, scaling, spalling, pop-outs, dusting, efflorescence, weathering, honey comb cracks, blow holes, scouring, and cold construction joints.

2.4Analytic 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. 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.

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: (i) importance: when comparing criteria with respect to their relative importance; (ii) preference: when comparing the preference of criteria for alternatives with respect to an objective; (iii) 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 (1/9 to 9) scale, can be established. Then weights of each element are calculated. The advantage of the AHP method is the easiness in the evaluation of weights, while considering for inconsistency.

2.5Multi-Attribute Utility Theory

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, dependant on the criteria. Generally, the utility function is either a non-linear or a linear function defined on the criteria space. The simplest (and most commonly used) analytical form is the additive form.

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

3. DEVELOPED STRUCTURAL PERFORMANCE ASSESSMENT MODEL

The new developed model solves the problem of lacking structural performance assessment model for the different subway systems' elements. The new developed methodology, outlined in Figure 1, consists of four main steps:

1) Identify a network hierarchy, and define the different structural elements: 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 elements. 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.

2) Identify the different structural performance factors and the resulting structural cracks and defects.

3) Assess the structural performance for the different subway elements:

- First the different cracks and defects scores for each element are evaluated by using the visual inspection reports.
- Second, using the AHP technique, the different cracks and defects importance weights are evaluated.
- Finally, using the MAUT mathematical tool, a Physical Performance Index (P_P) and a Functional Performance Index (P_F) are evaluated.

4) Using again the MAUT technique, an Integrated Performance Index (P_I) is evaluated that combines both the P_P and P_F.

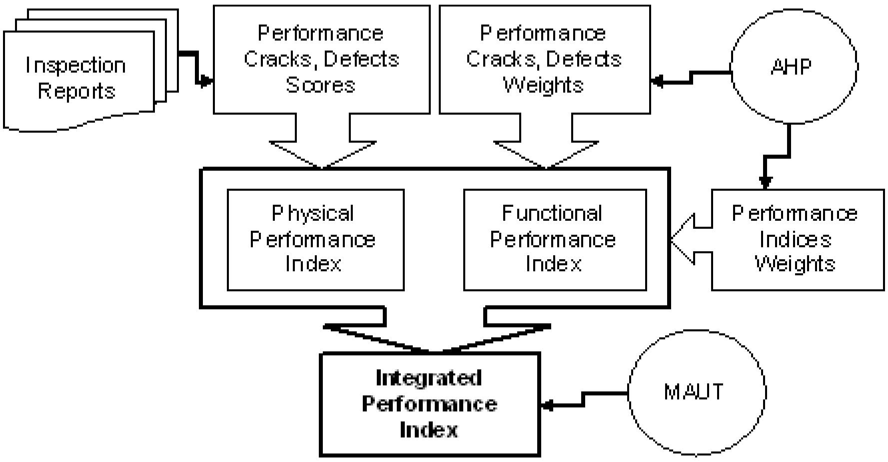

Figure 1. Outline of the Model

3.1 Subway Network Hierarchy

The developed model starts by identifying the subway network hierarchy. A subway network is composed of several lines. 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 structural elements.

Any generic station is made up of the following structural elements: (i) exterior and interior walls (including columns), (ii) exterior and interior slabs (including beams), and (iii) exterior and interior stairs. A typical tunnel is made up of the following structural elements: (i) dome or arch, (ii) side walls, and (iii) bottom slab. Auxiliary structures are mainly ventilation wells and dewatering wells, and mechanical ducts, and pipes opennings. 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 structural elements: (i) walls and (ii) slabs. The different structural elements hierarchy of the three types of subway systems are illustrated in Figure 2.

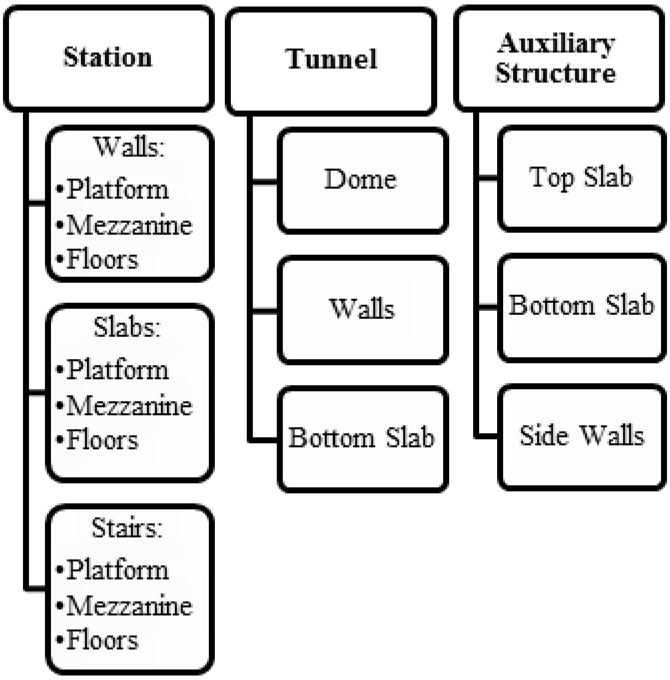

Figure 2. Subway Systems Elements Hierarchy

3.2 Structural Performance Assessment Factors

The structural performance of an element is identified as the in-service functioning of the element for a specified use. This refers to how effectively, safely and efficiently a structural element performs its mission at any time during its service life. A structural element performance state is reflected by two different indicators: the “physical condition state”, and the “functionality state”. The “physical condition state” relates to a element’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 element 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 proposed 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).

Based on the experience, literature review and *Canadian Standards Association* CSA-A23.3 *Concrete Design Handbook*, this model considers several factors for both the ‘Functional Performance’ index and the ‘Physical Performance’ index respectively. The structural performance assessment factors are illustrated in Figure 3.The factors that affect the functional performance are: (i) construction deficiencies, (ii) design deficiencies, and (iii) additional loads. Whereas the factors that affect the physical performance are: (i) fire resistance reduction, (ii), concrete and rebar degradation, and (iii) local damage and deflection.

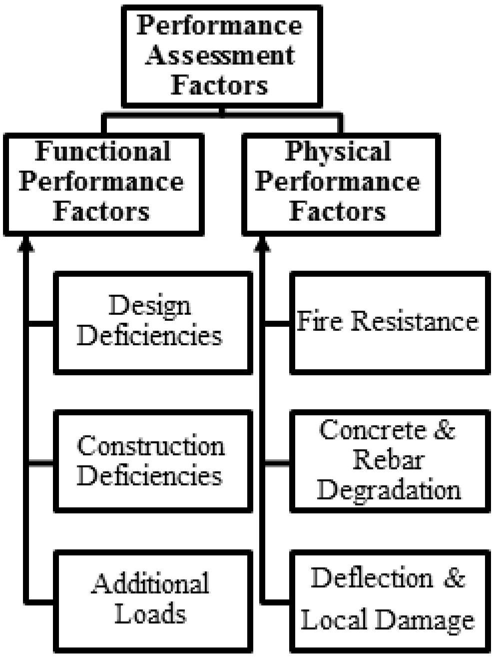

Figure 3. Structural Performance Assessment Factors

The above-mentioned functional and physical performance factors are not evaluated and quantified in this proposed model. However, they cause deficiencies in the elements, primarily structural cracks and defects. The structural cracks and defects are defined hereafter. These cracks and defects are identified based on the Canadian standards (Mailvaganam et al., 2000), british standards (CBDG), and American standard-related references (Milne et al., 2003). Furthermore, all of theses cracks and defects are considered in visual inspection reports of transit authorities, STM for example. Although structurally some cracks and defects are more important that others, constructing a rehabilitation management plan requires considering all possible cracks and defects. The main advantage of this approach is the easiness to quantify scores for the different cracks and defects.

3.2.1 Structural Cracks

9 structural cracks are the result of the Functional Performance Factors. 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. While, 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 identified in Table 1.

Table 1. Cracks Categories Definition

Crack Category	Crack Type	Crack Description
Design-Based	Stable movement of the element (SM)	SM cracks occur when the element moves in a stable manner.
	Continued increasing movement of the element (CM)	CM cracks occur when the element moves in a increased manner.
	Flexural deformation of the element (FD)	FD cracks occur when the element fails to resist flexural stresses.
	Shear cracks in the element (SHC)	SHC cracks occur when the element fails to resist shear stresses.
	Considerable vibration of the element (V)	V cracks occur after considerable vibration of the element.
Construction-Based	Water infiltration in the element (W)	W cracks are caused by infiltration of water in the element.
	Joint crack (JC)	JC cracks occur when the joint is not properly designed or constructed.
	Vertical misalignment of joint (VMJ)	VMJ occurs when a beam/column joint is not aligned vertically.
	Horizontal misalignment of joint (HMJ)	HMJ occurs when a beam/column joint is not aligned horizontally.

3.2.2 Structural Defects

16 structural defects are the result of the Physical Performance Factors. 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. While, mechanical-based defects are those that are related to local damage and fire resistance caused by physical or mechanical degradation. The defects under both categories are identified in Table 2.

Table 2. Defects Categories Definition

Defect Category	Decfect Type	Defect Description
Chemical-Based	Rebar corrosion (RCOR)	RCOR in concrete is an electrochemical process in which metallic iron is converted to the voluminous corrosion product ferric oxide.
	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 rebars due to their corrosion. It is also a separation along a plane nearly parallel to the surface of the concrete.
	Sweating (SWE)	SWE is water seeping through concrete that dissolves water-soluble elements (such as calcium hydroxide) in the concrete, which appear on the underside of the surface.
	Disintegration	DIS is the disintegration into small fragments or particles due to

	(DIS)	any cause.
	Stalactites (STAL)	STAL is a viscous gel-like material discharged through a crack in the concrete by the leaching water.
	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.
	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.
	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.
Mechanical-Based	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.
	Efflorescence (EFFL)	EFFL is a deposit of salts, usually white, formed on a surface, the substance having emerged from below the surface. Although it can be argued that the deposit of salt is a chemical reaction by itself, however this reaction is caused by a hairline crack, thus the cause is mechanical.
	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.
	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.
	Erosion (ER)	ER is the wearing of the concrete surface by the abrasive action of fluids containing suspended solids.
	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.
	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.
	Abrasion (ABR)	ABR can be defined as the process causing the surface to be worn away by repeated rubbing, rolling, sliding or friction.

3.3 Modeling Structural Performance Assessment

Next, the proposed model assesses the structural physical performance and functional performance indices for all subway systems' elements. First, the different cracks and defects are visually identified in each element, and respective scores are assigned. Crack and defect weights are evaluated using the AHP. Finally, using, the scores and the weights, the P_P and P_F are evaluated independently using the MAUT.

3.3.1 Scores of Structural Cracks and Defects

Structural cracks and defects in reinforced concrete structures can be generally evaluated using several well-known methods, such as visual inspection, and other non-destructive testing (NDT) methods. The proposed model scores on a defined scale, approved by most of the transit authorities, the different cracks and defects based on the inspector/structural engineer visual inspection. The scores identify how much the crack and/or defect is present in the element.

Although subjective in its nature, visual inspection is still the most widely used method, due to its low cost effectiveness. The model can be easily adjusted to any other NDT evaluation method. Nevertheless, it is important to stress that for subway systems, where the number of elements is extremely huge, other NDT methods would be time and cost consuming. Most transit authorities have few inspection reports, with irregular inspections (refer to data collection section), due to the big number of elements and systems in a subway network. Thus, visual inspection is the most common, and the most used method.

The scores of both the structural cracks and defects are based on a defined scale inTable 3. Then the scores are normalized into a performance index from 0 to 1.0. 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).

Table 3. Cracks and Defects Visual Inspection Score

Score	Crack/Defect Level	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.

3.3.2 Weights of Structural Cracks and Defects

All structural cracks and defects that affect the functionality of the element 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 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. 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 1:

$$\sum_{DbC=1}^{5} w_{DbC} = \sum_{CbC=1}^{4} w_{CbC} = \sum_{CHbD=1}^{8} w_{CHbD} = \sum_{MbD=1}^{8} w_{MbD} = 1.0 \qquad (1)$$

Where DbC = Design-based Cracks;

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

CbC = Construction-based Cracks;

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

CHbD = Chemical-based defects;

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

MbD = Mechanical-based Defects;

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.

3.3.3 Structural Performance Indices

Now, both the Functional Performance Index (P_F) and the Physical Performance Index (P_P) can be evaluated using both the cracks and defects normalized scores and the cracks and defects weights. The weighted scores can be used as attributes or utilities of the performances (either functional or physical). 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, because if one of the important cracks has a low index, it reduces the value of the performance index.

The Functional Performance Index (P_F) is defined in Equation 2:

$$P_F = \left(\prod_{DbC=1}^{5} \overline{S_{DbC}}^{\,w_{DbC}} \right)^{w_{Db}} \times \left(\prod_{CbC=1}^{4} \overline{S_{CbC}}^{\,w_{CbC}} \right)^{w_{Cb}} \qquad (2)$$

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:

$$P_P = \left(\prod_{CHbD=1}^{8} \overline{S_{CHbD}}^{\,w_{CHbD}} \right)^{w_{CHb}} \times \left(\prod_{MbD=1}^{8} \overline{S_{MbD}}^{\,w_{MbD}} \right)^{w_{Mb}} \tag{3}$$

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 Integrated Performance Index Evaluation

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. Independent use of the two indicators do not reflect an integrated performance measure or index and do not reflect a total structural performance. 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 again 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, and the sum of the weights equal unity, as definedin Equation 4:

$$w_{PF} + w_{PP} = 1 \tag{4}$$

The two indices P_F and P_P can be considered as independent attributes to the performance; hence the MAUT 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. This approach leads to the Integrated Performance Index (P_I), defined in Equation 5:

$$P_I = P_F^{\,w_{PF}} * P_P^{\,w_{PP}} \tag{5}$$

Equation 5 is very important because it takes into consideration extreme cases of P_F and P_P. If the P_F is low (severely deteriorated 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 element is not allowed, i.e. the asset managers must not let the element deteriorate below the threshold level of performance. This leads to the main observation, that if an element' performance is exactly equal to this limit, or threshold, it is in need of a major maintenance and repair. This last observation is clarified and justified if the manager analyzes carefully the scores shown in Table 3, which in turn is important. **Error! Reference source not found.**3 indicates that if a element has a visual score of '2', then this element 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 element to have a performance level below the score of '2' or 'POOR'? In other words, does the asset manager allow the structural element to have a 'Critical' performance level? The answer is straight forward: no infrastructure asset manager allows the element structural performance to be 'Critical' since it becomes dangerous to the public especially if the infrastructure (subway system) is a major public facility.

It must be stressed that for subway systems, all elements serve a certain facility, although some are not directly related to public. Hence, even a secondary stairway (that can be considered redundant to public security) cannot be allowed to perform below a critical level, because the facility dependant on this specific stairway is affected, and thus operation, or part of the mechanical or electrical system (for example) will stop performing.

Therefore, public infrastructure cannot have a 'Critical' level of performance, especially the subway system. 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, this 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.

4. DATA COLLECTION

The developed model is based on vital data, which primarily comprises the model inputs. These required data consist of two main categories: visual inspection reports and questionnaires. The inspection reports were provided by the *Société de Transport de Montréal* (STM) rehabilitation team (engineering unit). 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. Inspections were carried out in 1992, 1996, 1997, 1998, 2002, 2004 and 2005. In addition, not all structures were inspected. The reason behind the scarcity and irregularities is that regular inspections are expensive and dangerous. Data retrieved from the STM visual inspection reports are mainly: specific systems, different systems' structural elements (location, level, and type), cracks scores, and defects scores. The data retrieved were filtered and sorted in a database file for each type of structure (system), each inspection year, structural elements, floor level, and crack/defect type. The different cracks and defects count per element of the STM systems are tabulated in Table 4.

Table 4. Cracks and Defects Count per Element of Systems

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

It is clear that structural defects greatly outnumber the cracks, hence it can be concluded that STM elements (and systems) are well designed but are exposed to harsh and severe environment. The distribution of the different cracks and defects in STM systems is illustrated in Figure 4.

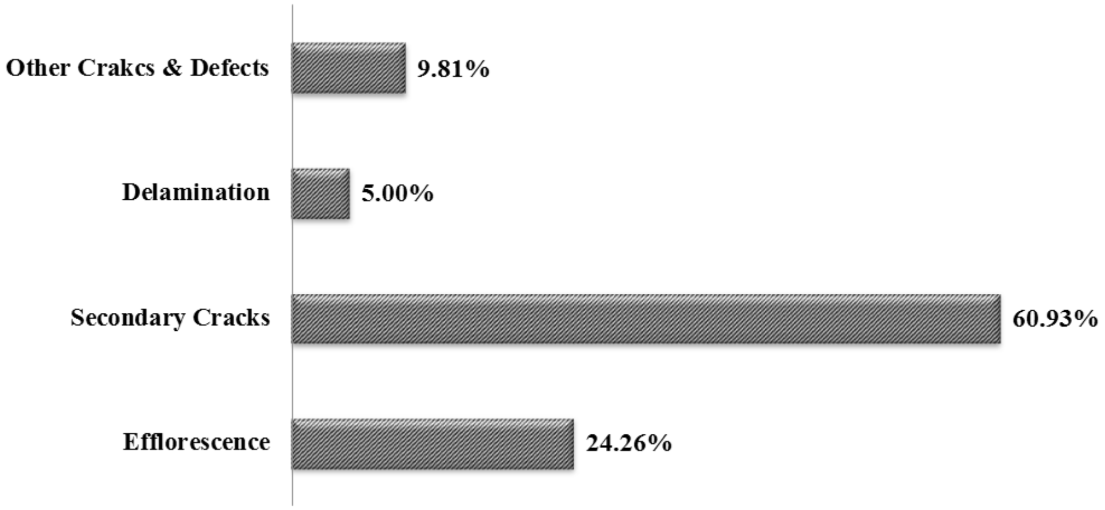

Figure 4. Cracks and Defects Distribution in Systems

It can be observed that 61% of the total cracks and defects are secondary 'Cracks' (C), whereas "Efflorescence" (EFFL) forms 24%, and "Delamination" (DEL) 5%; all three are defects. The rest (including structural cracks) form only 9%.Harsh external environment affected seriously the elements, and for that reason lot of defects are found.

Questionnaires serve to evaluate 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 AHP method. In order to apply the AHP calculation, comparison matrices among the different cracks/defects/indices are developed. The questionnaire is divided into three parts: part I compares using Saaty scale in matrices the structural cracks (both design-based and construction-based), part II compares in matrices the structural defects (both chemical-based and mechanical-based), and finally part III compares the physical condition state to the functionality state. The questionnaires are sent to practitioners in subway stations (engineers, inspectors and managers) and experienced structural engineers. The research has collected 32questionnaires of the AHP pair-wise comparison matrices to assess the weights of various factors, cracks, and defects. The respondents were experienced structural engineers, inspectors and transit managers. 9 out of the 32 were received from the STM managers, 16 from different structural designers, and 7 from structural rehabilitation engineers. The average year of experience of the respondents is 14 years. The weights of the different global cracks and defects weights are tabulated in Table 5.

Table 5. Structural Cracks and Defects Weights

Identification	Description	Average Weight	Identification	Description	Average Weight
Cracks			Defects		
SM	Stable Movement	2.71%	**RCOR**	Rebar Corrosion	14.95%
CM	Continued Movement	21.51%	**DEL**	Delamination	5.62%
FD	Flexural Deformation	13.61%	**SWE**	Sweating	2.42%
SHC	Shear Crack	18.79%	**DIS**	Disintegration	9.19%
V	Vibration	10.46%	**STAL**	Stalactite	5.09%
W	Water Infiltration	7.87%	**INC**	Incrustation	4.59%
JC	Joint Crack	9.77%	**AAR**	Alkali-Aggregate-Reaction	6.86%
VMJ	Vertical Misalignment	7.77%	**STRAT**	Stratification	4.94%

HMJ	Horizontal Misalignment	7.50%	**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%

The AHP weights results show that ‘continued movement’ is the most important type of crack, followed by ‘shear crack’, ‘flexural deformation’ and the rest. When ‘continued movement’ is recorded in a structural element, this means that the element fails to resist the applied loads and has surpassed elastic behavior zone. Whereas ‘shear crack’ is very critical because it can result in a sudden failure.‘Flexural deformation’ is less critical because rebar can yield and no sudden failure will happen. Consistency of the AHP matrices was checked, and found to be below 10%.

5. THE MODEL IMPLEMENTATION TO STM

A partial network of STM is selected for the implementation of the model. But due to space limitation, only four systems of the STM network are chosen for the developed model implementation. The implementation of this model to the STM systems aims at showing the functionality of the new model to any subway network.Table 6 shows the information of the systems used for the model implementation.

Table 6. STM Implementation Systems

Line	Systems Designation	Construction Year	Inspection Year
Orange	**STA 1**	1966	2005
	AS 1	1966	1995
	TUN 1	1966	2004
	STA10	1982	1996

The selected systems lie in the center of the STM network: the Orange and Green lines. This selection depends on the following criteria: (i) the Orange and Green lines are the oldest lines in the network; (ii) inspection reports are mostly available; and (iii) the stations and metro tunnels are highly utilized. The starting point of the model is to develop the network hierarchy. The systems hierarchy is illustrated in Figure 5.

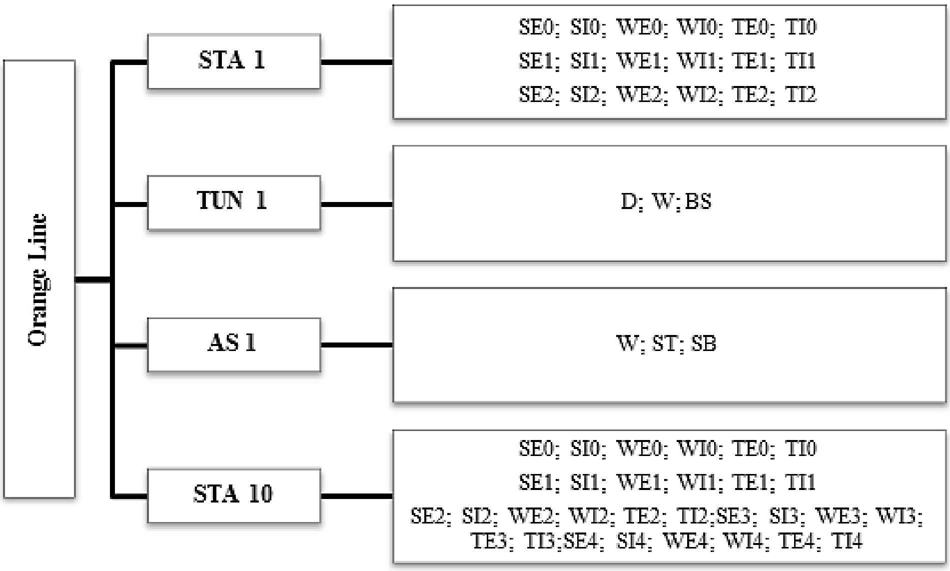

Figure 5. STM Systems' Hierarchy

Depending on the hierarchy, the physical, functional and integrated performance indices of each elements are evaluated (at the respective 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, it should be noted that not all elements are inspected. Thus, for a element that is not inspected, a score of 5 is assigned. The Functional Performance Index (P_F) is calculated using Equation (2), the Physical Performance Index (P_P) is calculated using Equation (3), and finally, the Integrated Performance Index (P_I) is calculated using Equation (4).

The detailed results for STA1 elements are tabulated in Table 7and showed in Figure 6, whereasTable 8 shows a summary of results for TUN1 and AS1 elements.

Table 7. STA1 Elements Performance Assessment

	Level 1						Level 2					
	SE1	SI1	WE1	WI1	TE1	TI1	SE2	SI2	WE2	WI2	TE2	TI2
P_{Fi}	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}	0.76	1.0	0.83	0.80	1.0	1.0	1.0	1.0	0.79	1.0	1.0	1.0
$\mathbf{P_{Ii}}$	**0.93**	**1.0**	**0.95**	**0.95**	**1.0**	**1.0**	**1.0**	**1.0**	**0.94**	**1.0**	**1.0**	**1.0**

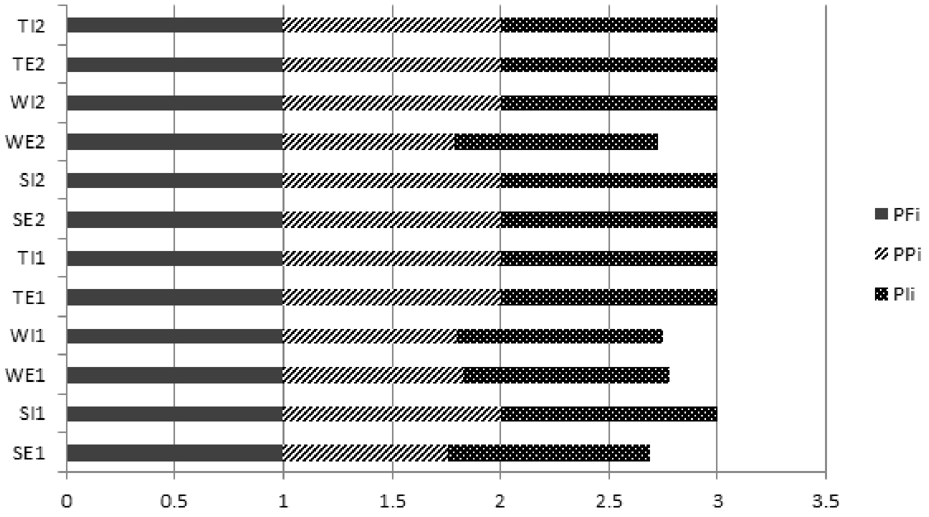

Figure 6. STA1 Elements Performance Assessment

Table 8. TUN1 and AS1 Elements Performance Assessment

Element	$t_i = 2004$		
	P_F	P_P	P_I
D	1.00	0.84	**0.96**
W	1.00	0.89	**0.97**
BS	1.00	1.00	**1.00**

Element	$t_i = 1995$		
	P_F	P_P	P_I
W	0.94	0.97	**0.95**
ST	1.00	1.00	**1.00**
SB	1.00	1.00	**1.00**

All three systems (STA1, TUN1, and AS1) show little deterioration. For instance, some of the STA1 elements show a small decrease of structural performance in 2005 (year of inspection). In addition 4 out of the 18 elements of STA1 are inspected and show deterioration (cracks or defects). Now, the TUN1 elements show also a small deterioration in 2004. The dome/arch (D) and sidewalls (W) are deteriorated, whereas the bottom slab shows no deterioration. The source of deterioration of the TUN1 elements comes mainly from the structural defects. However, AS1 wall (W) element shows in 1995 signs of major cracks, chiefly ‘shear cracks’ (SHC) and ‘vibration’ (V) cracks but to a lesser degree.

Table 9 shows the results of STA10 performance assessment. STA10 results will be used in further analyses.

Table 9. STA10 Elements Performance Assessment

Element	P_{Fi}	P_{Pi}	P_{Ii}
SE0	1	1	1
SI0	1	1	1
WE0	1	0.9	0.97
WI0	1	0.9	0.97
TE0	1	1	1

TI0	1	1	1
SE1	1	0.8	0.95
SI1	1	0.8	0.95
WE1	1	0.8	0.95
WI1	1	0.8	0.95
TE1	1	0.8	0.95
TI1	1	0.7	0.92
SE2	1	0.8	0.95
SI2	1	0.8	0.95
WE2	1	0.9	0.97
WI2	1	0.8	0.95
TE2	1	0.8	0.95
TI2	1	0.7	0.92
SE3	1	1	1
SI3	1	1	1
WE3	1	0.8	0.95
WI3	1	0.8	0.95
TE3	1	0.8	0.95
TI3	1	0.8	0.95
SE4	1	1	1
SI4	1	1	1
WE4	1	1	1
WI4	1	1	1
TE4	1	1	1
TI4	1	0.8	0.95

STA10 is chosen in this implementation in order to analyze the effect of different construction years to the integrated performance index. STA10 was inspected in 1996 while constructed in 1982 (14 years of difference) and repaired in 2010 (28 years after construction). It seems that many structural problems are encountered in this particular station. Problems are mainly due to external harsh environmental effects. But, what makes the problem difficult the fact the this deterioration is reached only after few years from construction date. It is thus observed that the smaller difference between the construction and the first signs of loss of performance (deterioration), the higher the deterioration rate. This fact is true, because the inspection shows rapid deterioration. As a matter of fact, the station STA10 was closed in 2010 due to major repair works.

6. SENSITIVITY ANALYSIS

Two sensitivity analyses are performed on the developed model. The first one is done in order to assess the effect of change of cracks and defects scores on the integrated performance index, and the second one analyzes the different 'year of construction' effect.

The first sensitivity analysis considers the change in cracks and defects scores to be between -40% and 0% of the original scores. This change in the scores should reflect the uncertainty and subjectivity in assigning a visual inspection score by the engineer or inspector. The @RISK software is used for this type of analysis. Three new systems on the green line are chosen (STA4, TUN4, and AS4). One element for each system is also used. Table 10 summarizes the sensitivity analysis results, while Figure 7 illustrates the change in P_I versus the change in score.

Table 10. Sensitivity Analysis Results

Scores (% Change)	WE4 (STA4)	W (TUN4)	W (AS4)
-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

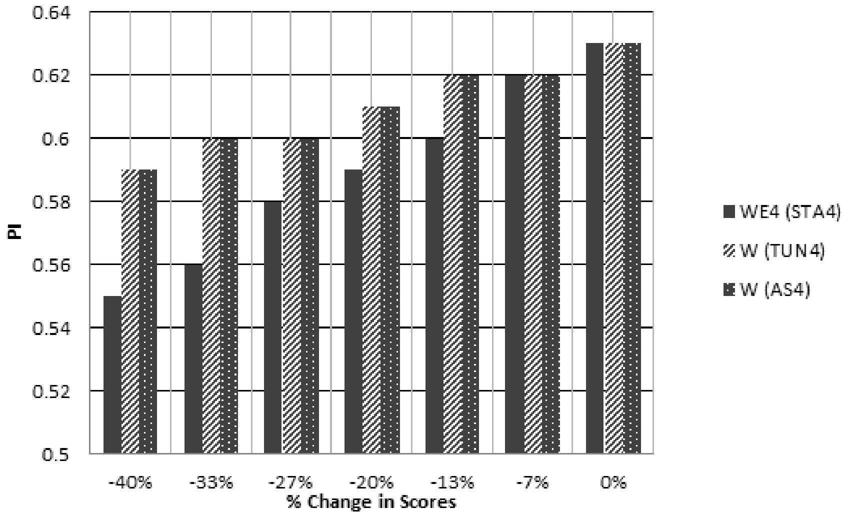

Figure 7. Sensitivity Analysis Figure

It is observed that the change in the integrated 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 scores. This means that the performance index is sensitive to the score, however the weight of the defect, and the defect type affect the index as well. Hence the score is not only the sole criteria affecting the index.

The second sensitivity analysis considers the effect of the difference between the 'year of construction' and the 'year of inspection' versus the P_I at the inspected year. 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). Several stations (i.e. STA7, STA8, STA9, and STA10) are chosen for this analysis, which are constructed in 1966, 1976, 1978 and 1982, respectively. STA7, STA8, STA9, and STA10 inspection years are 2005, 2004, 1996 and 1996, respectively. It is observed that for some of those stations the inspection and construction years are close, STA10 is a good example, STA9 is another one. For this additional analysis, an Integrated Deterioration Rate is evaluated using Equation 5:

$$IDR = \frac{1.0 - P_I}{Inspection\ year - Construction\ year} \quad (5)$$

Where: IDR = Integrated Deterioration Rate

And P_I = Integrated Performance Index at the inspected year.

1.0 = Integrated Performance Index at the construction year.

Table 11shows this additional sensitivity analysis results for some of the major elements for the above-mentioned stations.

Table 11. Additional Analysis Results

Station	Construction year	Inspection year	Difference	Major element	PI	IDR
STA7	1966	2005	39	WE1	0.9	0.26%
STA8	1976	2004	28	SE2	0.85	0.54%
STA9	1978	1996	18	SI3	0.82	1.0%
STA10	1982	1996	14	SE2	0.78	1.57%

It is observed that the lower the difference of years between construction and inspection, the higher the IDR, or the deterioration rate. This last observation confirms our discussion about STA10 in the above-mentioned implementation section.

7. MODEL TESTING

This model is hard to validate mathematically. Thus,it was tested empirically on STA inspection results. Hence, STA1 was renovated in 2005, while the model shows Pis higher than the threshold (0.4). On the other hand, STA10 showed in 1996 signs of deterioration (14 years after construction), and for a second inspection much higher deterioration (lower than the threshold). In 2010, STM closed this station for major repair works. This particular case shows matching between model results and real life situation.

8. CONCLUSIONS

A new model is developed to assess the physical and functional performance indices for elements 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 element. Data were collected from different inspection reports and questionnaires. Secondary cracks and efflorescence are the most encountered defects found in the inspection reports. Continued movement is to be considered the most important crack as well. The model is implemented on some systems of the STM network. The systems element constructed in 1966 and inspected in 2005 show little deterioration. On the other hand, the systems element constructed in 1982 and inspected in 1996 showed higher and fast deterioration. It is also observed that the main cause of deterioration of STM systems elements is the external harsh environment. Sensitivity analysis is also carried out, and it resulted in a 15% change of performance index for a 40% change in cracks and defects scores.

The developed model contributes to the better solution of the major problem of subway network performance modeling, mainly the lack of integration of condition and safety in a unique deterioration model and the limited scope of existing subway models.

9. ACKNOWLEDGEMENT

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