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# AN IMAGE-BASED DATA MODEL FOR SUBWAY CONDITION ASSESSMENT

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**Abstract:** The Canadian Urban Transit Association (CUTA) estimated that transit infrastructure needed a total of 53 Billion Canadian Dollars in 2013. Subway networks form an essential part of the public transportation infrastructure. Several surface defects may develop on subway infrastructure facilities, of which the most commonly identified are cracks, scaling, spalling, delamination, moisture marks, and efflorescence. These distresses participate not only in degrading the structure aesthetically, but in increasing the deterioration mechanisms of its components, taking into account the severe environmental conditions and continuous heavy loads that the structure is subjected to during its service life. High deterioration rates may cause the closure of subway system, therefore condition assessment of subway networks represents a crucial yet challenging task in the sustainability of a sound concrete infrastructure. Visual inspection techniques are considered the principal methods used in the condition evaluation of civil infrastructure. These methods are time-consuming, expensive, and depend inherently on subjective criteria. Several models have been proposed by previous researchers to assess the condition of subway systems. However, all of the developed methods were dependent on the visual inspection reports, hence they lacked the objectivity in quantifying and estimating the severity of defects. Therefore, a robust model that can detect the distresses and compute their severity needs to be developed. This paper defines the details of the recently introduced procedure based on image processing and assessment techniques. A five phased process is presented for accurate condition assessment of subway networks. The developed methodology utilizes data acquisition tools for collecting images of different elements in subway networks. Multiple algorithms are utilized to detect, interpret and measure surface defects, such as binary transformation, histogram equalization, image dilation, and hole filling. A case study from Montreal subway system was used to exemplify the application of the developed method. The results prove the potential benefits of the proposed methodology in identifying and quantifying surface defects. This research concludes the reliability of image-based data model in terms of accuracy, efficiency, and ease of analysis.

**Keywords**: Image Processing, Subway System, Inspection, Condition Assessment

## 1 INTRODUCTION

Public transit infrastructure plays a vital role in the economy, prosperity and the well-being of people. Subway networks form a fundamental constituent of the public infrastructure. Statistics show that the amount of passengers choosing the subway system for their daily travel is on the rise. According to the American Public Transportation Association (APTA) Fourth quarter report (APTA, 2013), in New York

City, 2.7 billion trips took place in 2012, while in the case of Montreal, that number reached around 357 million trips. (APTA 2013).

The increasing demand for underground transportation in addition to other factors will participate in the deterioration of subway systems. These factors include but are not limited to, the aging of infrastructure facilities, harsh environmental conditions, heavy loading, and deferred maintenance and rehabilitation plans. The high deterioration rates and the growing demand on metro systems, make the condition assessment procedure a critical safety issue. Accordingly, a reliable condition assessment method has become a vital task yet a necessity to ensure the sustainability of the structure.
Condition assessment of subway networks provides inputs for planning future maintenance activities. In both Canada and the United States, the main approach to evaluate the condition of subway systems, is based on visual inspection (VI), which is time-consuming, expensive, and depends regularly on subjective criteria. Automating the current practice is expected to provide more objective, accurate, quantitative results which will eventually lead to enormous savings in time and money. Among several damage detection techniques, the use of optical devices such as digital cameras and image processing methods are promising methodologies. One automation aspect is the detection of spall defects which develop on the surfaces of concrete structure. This paper aims at developing an automated assessment model for subway networks based on image processing algorithms and non-destructive evaluation (NDE) technologies. The model performs damage identification and quantification of spalling on the external surface of concrete. It provides a systematic approach for the identification of spall areas through different image enhancement algorithms, such as histogram equalization, image thresholding and mask processing. The output of this research is a decision support tool, expected to assist the infrastructure managers and civil engineers in their future plans and decision making.

## 2 BACKGROUND AND LITERATURE REVIEW

In the literature review, several efforts have been made to evaluate the condition of subway networks. Semaan (2006) has developed a condition assessment model to diagnose and assess the conditions of subway stations. This model has defined functional criteria and applied the Analytic Hierarchy Process (AHP) to calculate their weights. Then, the Preference Ranking Organization Method of Enrichment Evaluation was used to find the aggregation of weights and scores, and finally Station Diagnosis Index (SDI) was calculated using the Multi-Attribute Utility Theory (MAUT), and a condition scale for the evaluation of each station was proposed. This model was applied later on Montreal Metro stations. Another model was proposed by Semaan (2011). This model was developed to assess the performance of subway network, it has started by the hierarchy identification of subway network. Then, the physical and functional performances of each component in the network were assessed and integrated into one performance index using the AHP and MAUT theory. Performance prediction curves for all the components in the network were constructed using a Weibull reliability function. Moreover, this model has evaluated the performance of various systems, lines and the whole network by the use of the series-parallel system technique and was implemented in the Montreal subway network.
Kepaptsoglou et al. (2012) have developed a model to evaluate the functional condition of subway stations, this model was applied to Athens Metro systems. Several criteria and sub-criteria were allocated to every station. The AHP and Fuzzy AHP were utilized to rank the sub-criteria according to their significance to the station's operational phase. The sub-criteria were weighted according to their significance to the station's operational phase and they were evaluated on a scale of 0-5 by Athens transit authority. Then, their scores were aggregated with the use of MAUT to get the Metro's Condition Index. This model was developed solely for the condition assessment of subway stations. In order to improve the previous model and achieve the interdependencies among its criteria, Gkountis and Zayed (2013) have applied the Analytic Network Process (ANP) and have used the same 0-5 scale. The additive MAUT was implemented to acquire the station's condition index.

Abu-Mallouh (1999) has developed a "Model for Station Rehabilitation Planning" so called "MSRP" in an effort to improve the "Point Allocation Model" implemented by the MTA NYCT. The MSRP has considered the same functional and social criteria used by New York Transit Authority. The Analytic Hierarchy Process (AHP) technique was applied to obtain weights for the stations. For rehabilitation planning, a

powerful optimization technique (Integer Programming) was used to allocate budget for stations. The weights and budget allocation were later used to prioritize stations for rehabilitation. In fact, the MSRP is a budget allocation model rather than a condition assessment or a deterioration model and it is only limited to the evaluation of stations. Furthermore, it did not use real collected data for the validation process. Faraan (2006) has proposed a model "maintenance and rehabilitation planning for public infrastructure" known as "MRPPI" and implemented in the Montreal subway stations. This methodology has considered the life-cycle cost analysis of the structural elements in the infrastructure. It has applied Markov Chains theory to evaluate the deterioration of the elements and used transition probability matrices as input variables to the model. Consequently, Genetic Algorithm optimization technique was utilized to minimize the life cycle cost after considering a series of intervention actions.

Derrible and Kennedy (2010) have developed a model, the objective of which was to improve the efficiency and ridership of Toronto Metro network by assessing its performance as well as comparing it to other subway networks. The model was developed by computing three major factors including coverage, directness and connectivity. Numerous variables were considered in the computing process, including covered area, ridership, possible transfer options and number of lines. Marzouk and Abdel Aty (2012) have proposed a Building Information Modeling (BIM) framework for the maintenance of subway infrastructure. Various asset management indicators were included in the body of this research, such as structural integrity, mechanical systems, HVAC systems, electrical system and user-related indicators. The model has aimed at offering a solid ground by proposing BIM flowchart that considers the indicators as prepared inputs to a comprehensive BIM/Asset management model.

Abouhamad (2014) has developed a risk-based asset management framework for subway networks. The study has proposed two main models namely; fuzzy risk index model and risk-based budget allocation model. In the first main model, risk was evaluated using three sub models; probability of failure, consequences of failure and criticality index. Probability of failure for several structural components was evaluated based on inspection reports and Weibull reliability function. Consequences of failure were evaluated through seven attributes, such as revenue loss, replacement/repair cost, etc. Consequently, criticality index was computed using seven criteria, such as number of lines, number of exits, etc. And finally, the second main model was proposed which is a budget allocation model. It has delivered recommendations to prioritize stations for rehabilitation action and applied two sets of variables.

In all of the aforementioned studies, the models were subjective and dependent on the visual inspection reports. Therefore, they have lacked the objectivity in quantifying and estimating the severity of defects. As a result, more accurate condition assessment techniques are essential in order to acquire reliable results and improve the quality of inspection in concrete infrastructure. This paper presents an auto inspection system that is capable of accurately detecting, analyzing, and evaluating the condition, as well as reducing the inspection time and cost in subway systems. The frame work of the methodology is based on image processing techniques.

## 3 RESEARCH METHODOLOGY

The main concept of the imaging data model is to acquire digital images of surface defects in subway network, and apply different image processing techniques to make these defects more distinguishable and suitable for computing purposes. Figure 1 presents the model architecture which is based on applying different image processing algorithms.

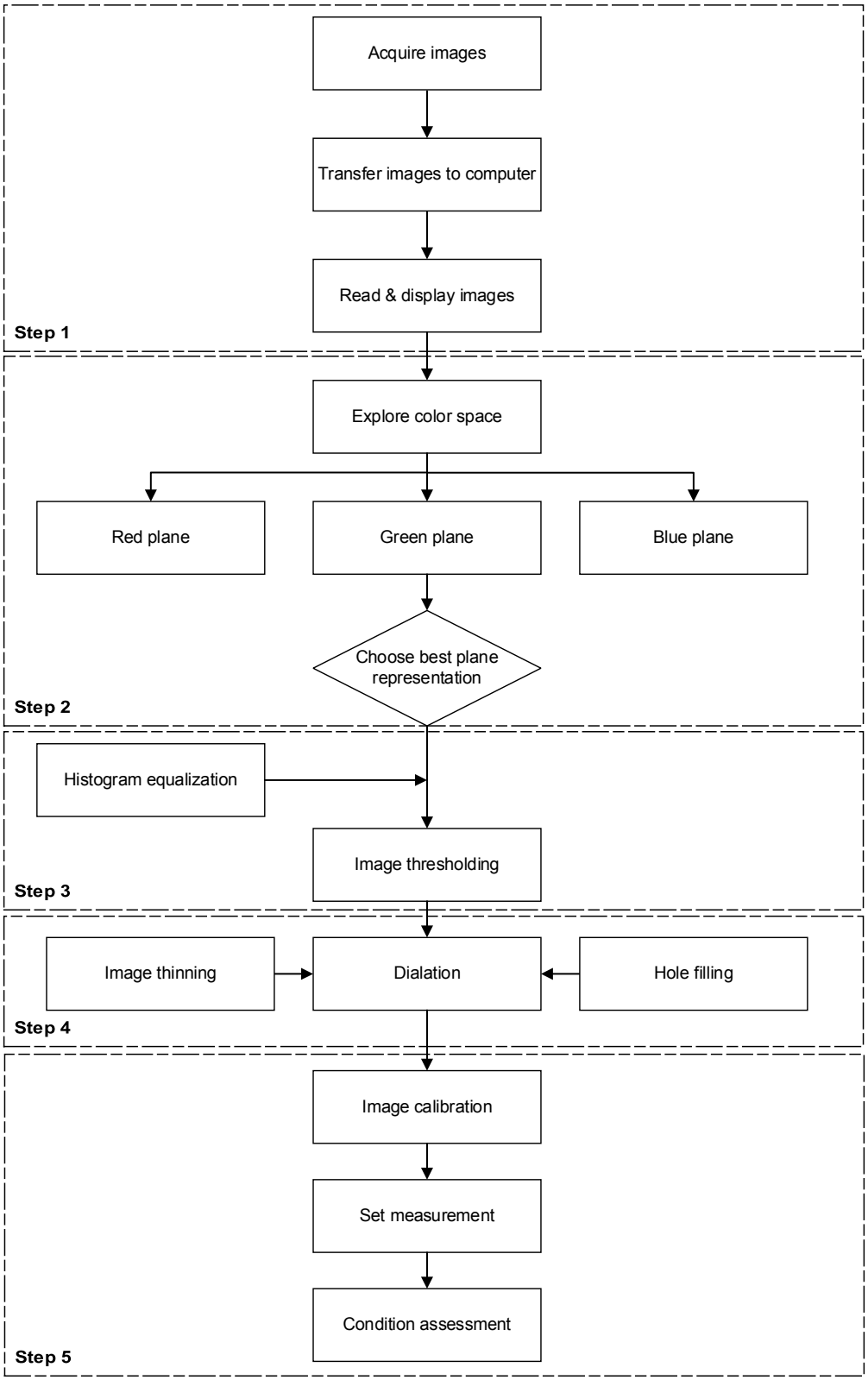
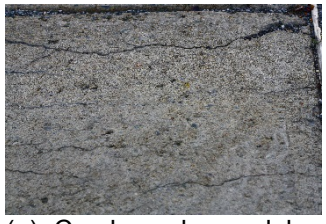



Figure 1: Image data analysis and assessment model

**Step 1**

Images of the components of subway system were obtained using a digital camera. The images contained different visible defects on the structure's surface, such as cracks, moisture marks, scaling, spall …etc. as shown in Figure 2. A digital camera (Canon EOS Rebel XS, 10.1-magapixel) with a high resolution of 2592x3888 pixels was employed to acquire images for concrete surfaces. Afterwards they were transferred to the computer to be processed. This research takes spall defects that are visible on subway concrete surfaces as an example for the proposed methodology.



(a) Cracks on lower slab

(b) Moisture marks on upper slab

(c) Scaling on upper slab

(d) Spall on lower slab

Figure 2: Different surface defects in subway networks

**Step 2**

The term "image" could be defined as a two dimensional (2D) function $f(x,y)$, where $f$ denotes the gray-level or intensity of the image at spatial coordinate point $(x,y)$ which corresponds to each pixel in the image (Gonzalez and Woods 2008). A digital image could be represented as a matrix which includes a large number of elements called pixels. Generally, the images are either gray-level images or color images. A gray-level image is a black-and-white image which has one matrix only, and the elements of the matrix represent pixels' intensity values. Normally, matrix values in a digital image range from 0 to 255. A color image is an RGB image which is formed of three planes; red, green, and blue as depicted in Figure 3. It is necessary to split the RGB image into three planes in order to choose the plane which demonstrates the best visualization and to facilitate image enhancement and detection processes. The acquired images in this research were RGB images, they have been split into the three planes and the red plane was selected so that it can be processed later.

Red Plane

Green Plane

Blue Plane

Figure 3: The three planes of RGB image

**Step 3**

One of the most significant methods, is thresholding the image through segmentation. Thresholding is the method of separating the object of interest from the background of the image. It is a binary transformation of the gray-level into either black or white intensity levels. Accordingly, matrix elements of a binary image have either zero or one value. Figure 4 shows a binary transformation of an image.

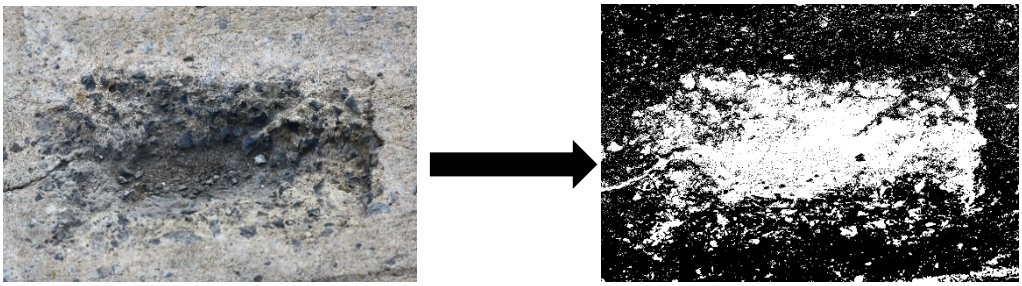


Figure 4: Binary transformation of the image

The selection of the best threshold value of a gray-level image is correlated to plotting its histogram. Therefore, the position of best threshold value will be specified. Figure 5 illustrates a histogram of a gray-level image. The horizontal axis represents the intensity of gray-level and the vertical axis is the frequency of occurrence of a pixel value in the image.

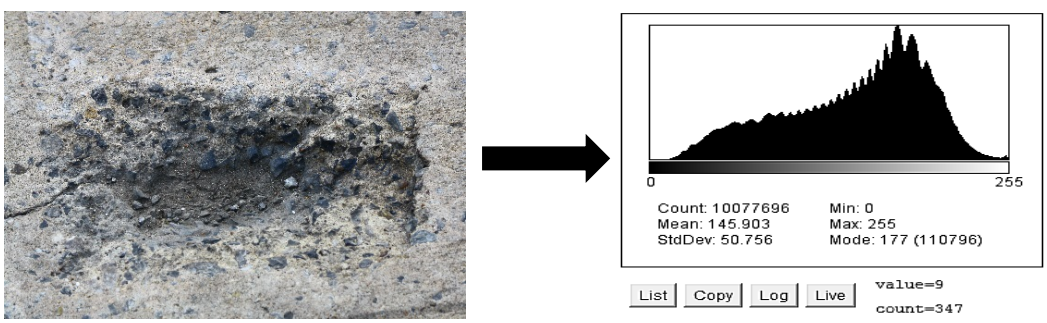



Figure 5: Gray-level image and its histogram

**Step 4**

It is quite useful to apply some morphological algorithms on the binary image, especially for the detection of boundaries. There are other techniques and filters which can be used concurrently with these algorithms, such as hole filling, thinning, thickening, etc. One of the basic algorithms which is used for filling holes in the image is developed on incorporating dilation, complementation, and intersection. Dilation is the process of thickening the boundaries of an object in a binary image (Gonzalez and Woods 2008), hence the object will be clearly visualized. Figure 6 depicts the processed image after using different morphological operations on the binary image including thinning, dilation, and hole fillings.

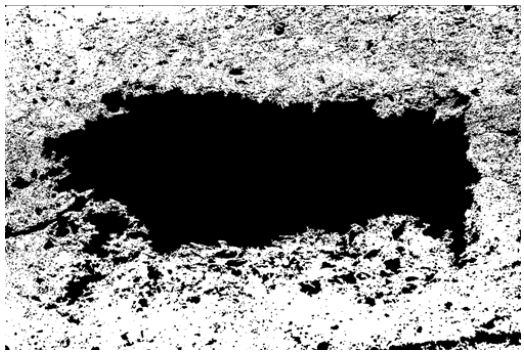


Figure 6: Dilated image

**Step 5**

Before evaluating the condition of any element using image analysis, the images should be calibrated by setting the appropriate scale. A commercially available software ImageJ was used for processing and scaling the images. Prior to uploading, processing and scaling the images by the software, the length of spall (object) has been measured in situ so that it can be set as an entry data in the software. Thereby pixel values will correlate with actual measurements allowing all possible measurement to be done on the image. Subsequent to scaling the image, the defect has been selected, hence it is possible to obtain feature attributes such as area, percentage area, perimeter, width, lengths of major and minor axes, mean, standard deviation, etc. Figure 7 illustrates scaling the image and selecting the defect using the analysis software. For the purpose of evaluating the condition of a component in this research, only the spall area and its percentage in that component were taken into consideration.

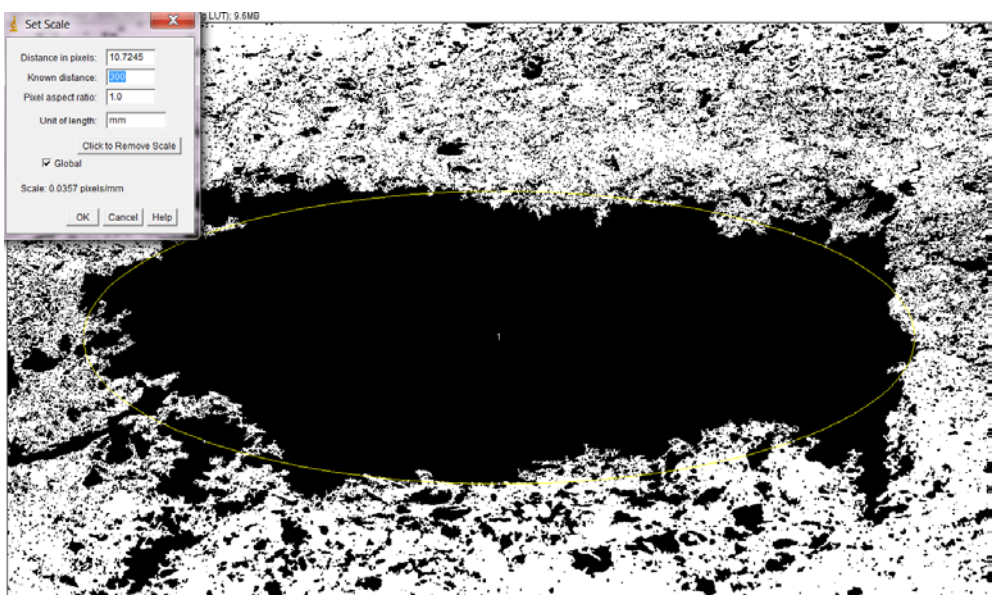



Figure 7: Setting image scale and selecting the object

## 4 RESULTS FROM MODEL

The proposed imaging data model was applied on a station in Montreal's subway network. A total of 50 images were acquired for the upper and lower slab surfaces of the station for the objective of quantifying and measuring the defect (spalls). Table 1 summarizes the assessment results for a sample of 10 images acquired for the station slabs. These images targeted spall distress which is visible on the components'

surfaces. The defect (spall) area and spall percentage in each image were calculated using the proposed model. For example, from table 1, image number 6 which has been used in the image processing of this research, was processed by the model and demonstrated the largest area of 224 $cm^2$, thereby acquiring 57% of the whole slab area and considered a severe defect. Whereas, image number 3 showed the smallest area of 6.88 $cm^2$, thus acquiring 1% of the whole slab area and considered as a minor defect. The proposed assessment methodology was validated by taking actual measurements for the spall defects in Montreal subway station. Then area and spall percentage calculations were performed on each defect and compared to the calculations obtained from the model. The results showed that image-based model had an accuracy of 98% in detecting, measuring and evaluating surface defects in subway infrastructure.

Table 1: Assessment results of a subway station in Montreal

| Image number | Slab location | Spall Area $(cm)^2$ | Spall percentage |
|---|---|---|---|
| 1 | Upper | 10.20 | 2 |
| 2 | Upper | 57.33 | 15 |
| 3 | Upper | 6.88 | 1 |
| 4 | Lower | 111.27 | 28 |
| 5 | Upper | 34.14 | 9 |
| 6 | Lower | 224.00 | 57 |
| 7 | Lower | 30.29 | 8 |
| 8 | Upper | 88.54 | 22 |
| 9 | Upper | 27.67 | 7 |
| 10 | Lower | 158.64 | 40 |

## 5 SUMMARY AND CONCLUSION

This paper presented a framework which applies image processing techniques for the detection and quantification of surface defects in subway networks. The imaging data model was realized by following five steps, each step comprised the utilization of several algorithms. In the first step, images for different surface defects have been acquired by a digital camera, then they were transferred to the computer to be processed. Step two included exploring the color space and extracting three planes for the purpose of selecting the best visualized plane to be further processed. Thresholding the gray-scale image and plotting its histogram was the approach applied in the third step to be followed by using some morphological operations such as image thinning, dilation and hole filling in the fourth step. And finally, the image has been calibrated and feature vectors such as area, percentage area, width, etc. were obtained. The proposed methodology was applied on segments of Montreal's subway system. The case study results were compared to the results taken from ground measurements, thus demonstrated a high accuracy of 98% in assessing the severity of defects. This proves the robustness of the proposed model in enhancing the quality and consistency of condition assessment, as well as, reducing the cost and time required to inspect subway networks.

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