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# Tunnel Asset Management (TAM) Program Application for High Risk Structural Components

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**Abstract**

Tunnel is a constructed structure providing longitudinal space in underground. Main purposes of tunnel are for various utilities and transportation corridors. Engineering of modern tunnel structure emphasizes on sustainability aspects including safety, efficiency, environmental stewardess,social responsibility, resiliency and economy. However, enhancement of sustainability in existing tunnel systems is also imminent through remaining life cycle. Many existing tunnel systems are currently approaching or already exceeding their design life. Invisibility and limited access of many structural components make tunnel inspection problematic and forgotten.Eventually public safety becomes uncertain. Application of tunnel asset management program is the first step to enhance public safety of existing tunnel system. This paper describes a conceptual frameworkdevelopment and application plan for a tunnel asset management program focusing on high risk structural components inspection and condition inspection technologies.

**Keywords:** Tunnel, Asset Management, Condition Inspection

## 1. Introduction

The main functions of tunnel structure are used for roadway and railroad transportation, liquid storage and transmission, and space for other utilities. The demand of tunnel system has quickly expandedduring the last few decadesdue to limited natural corridor and space, design and construction technology development, and minimizing environmental impact.

This paper lean toward tunnel asset management application for transportation tunnel because the tunnel is always exposed to general public and has high impact on service criticality.

Typical structural components of tunnelsare, but not limited to, structural lining, drainage system, ceiling panel and frame, ventilation and mechanical system, electrical and lighting system, fire protection and emergency escape system.Structural lining prevents fall-out of exposed ground excavation.Drainage system drains surface water collection, groundwater infiltrations, and water from maintenance and cleaning activities. The ventilation system maintains appropriate internal air quality and plays an important role for smoke ventilation. In the United States, accident related fire occurs at least once per yearin roadway tunnels (NCHRP[b], 2011). Lighting system specifically atthe tunnel entrance reduces the light contrast effect called black hole between daylight and inside tunnel. Emergency escape systemprovidessafe exit corridorto save lives for large and long transportation tunnel systems.

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The inspection of tunnel components, as a part of tunnel asset management program, is a broad topic which consists of the inspection of all above structural components. The tunnel systems will be categorized into sub-groups of main components and the inspection plan requiresunique considerations of each component. Visual inspection is the least expensive and convenient inspection method, however many components including structural ceiling panels and anchors are not easily accessible for the visual inspection. In 2012,collapsingof more than 300 structural precast concrete ceiling panelskilled nine people and caused significant property damage in Sasago Tunnel, Japan. Each precast ceiling panel weighs approximately 1.2 tons. Another case was reported atI-90 central Artery/Tunnel (CA/T) in Boston in the United States, collapse of more than 10 structural ceiling panels weighing 2000 kg/each killed one passenger in 2006 (NTSB, 2007). Both cases were caused by defects of metal anchor bolts and chemical adhesion securing ceiling panel, metal frame, and concrete tunnel lining. These two cases are good examples that indicate the importance of tunnel asset management including appropriate inspection and condition monitoring technology implementation for the existing structure components.

Tunnel asset management (TAM) has been defined as asustainable approach to managing the overall operation of tunnel systems to minimize life cycle cost, manage risks effectively, and improve public safetythrough a conceptual framework (Zamenian and Koo, 2013). This paper is intended to provide TAM model framework and its application structure. Advanced technologies forstructural component inspection and monitoring are introduced as a part of TAM modelimplementation.

## 2. Previous Asset Management Development

Asset management for civil infrastructure systemsis a developing domain to ensure minimum life cycle cost of operation and maintenance, safety, and maximum life span of existing structures and appurtenances to support sustainable development of modern civilization.Civil infrastructure industry has made significant progress in asset management program and inspection manual development,but actual asset management application plan is still in its infancy and needs more attention.

During past decades, roadways and bridges have received more attention in comparison to other transportation assets (Hensing and Rowshan, 2005). Bernhardt et al. (2003) studied on other infrastructure assetssuch as embankments, tunnels, retaining walls, culverts and drainage systems to develop asset management. They stated that the most asset management programs focused on pavement and bridge.Asset Managers did not effectively assess the condition of other assets. Akofio-Sowah et al. (2014) studied the current practice of asset management for other transportation assets. They concluded that the other assets typically not a part of existing intransportation asset management programs.Too (2012) studied rail, airport, and seaport systems and determined the gaps in different infrastructure asset management systems. They proposed an integrated dynamic capability models managing various tasks includingcapacity, option evaluation, procurement, maintenance, and information to bridge the gaps in between infrastructure asset management systems.

The United States Department of Transportation (USDOT) has defined tunnels as one of physical asset inventories for its highway asset management framework.

A typical highway asset management framework should comprise goals and policies, asset inventory, condition assessment and performance modeling, alternative evaluation and program optimization, short-term and long-term plan, program implementation, performance monitoring, and budget allocations.Figure 1 demonstrates the basic asset management components and configuration (USDOT, 1999).

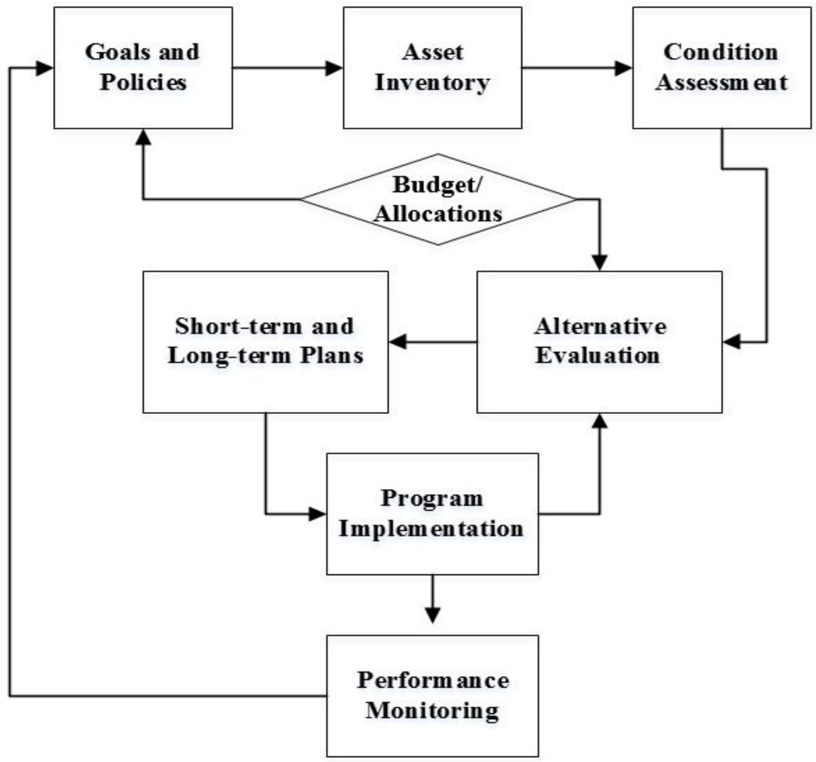


**Figure 1. Highway Asset Management Framework (USDOT, 1999)**

More than 300 highway transportation tunnels exist is the United States with the average age of more than 50 years (NCHRP[b], 2011). The formation oftunnel asset management program in the United States can be identified by two manuals; 1) the*Highway and Rail Transit Tunnel Inspection Manual; and 2)* the *Highway and Rail Transit Tunnel Maintenance and Rehabilitation Manual*, initiated from the Federal Highway Administration in conjunction with the Federal Transit Administration (FHWA[a], 2005).

Both manuals introduces the fundamentals of inspections for tunnels components such as of structural systems, mechanical systems, and electrical systems, as well as provides guidelines for inspection frequency, inspector qualifications, standardized condition definitions for various types of tunnel construction and equipment, procedures for rating elements within a tunnel, and recommended documentation. According to the National Cooperative Highway Research Program (NCHRP[a], 2011), several state departments of transportations including Colorado, District of Columbia, Virginia, and Washington commonly share the Highway and Rail Transit Tunnel Inspection Manual as their inspectionreference.On the contrary, the Massachusetts and the Port Authority of New York and New Jersey developed their own manual for tunnel inspection. In addition, the FHWA developed the Tunnel Management System (TMS) software along with the manuals for the data collection and monitoring tunnels work orders.Unfortunately the application of TMS software did not gain sufficient popularity (NCHRP[a], 2011).

The United States Department of Defense (USDOD) has developed its own tunnel inspection manual. USDOD tunnel inspection manual defines three basic steps for the inspection of highway tunnels; level one inspection method, level two inspection method, and level three inspection method. The purpose of the level one inspection is to detect observable defects in a tunnel and its portal structure. The level one inspection process consists of an inspection of readily accessible parts of the tunnel and portals as observed from the tunnel floor and entrance to the tunnels.

In this level the recorded observations by the field inspector are designed to create a historical data base. The purpose of the level two inspection process is to obtain additional information or measurements concerning a defect observed during the level one inspection process (USDOD,1995).

European countries follow the Permanent International Association of Road Congress (PIARC) manual of the Tunnel Management System (TMS). The TMS has an organized approach toward the asset management program and was developed based on the experience of ten European countries. The components of TMS includes administration manual, inventory manual, technical operation manual, maintenance and inspection manual, traffic management manual, and equipment and spare part manual (PIARC, 2005). The inspection and maintenance flowchart for their tunnel works are very comprehensive in compare to other countries as shown in Figure 2.

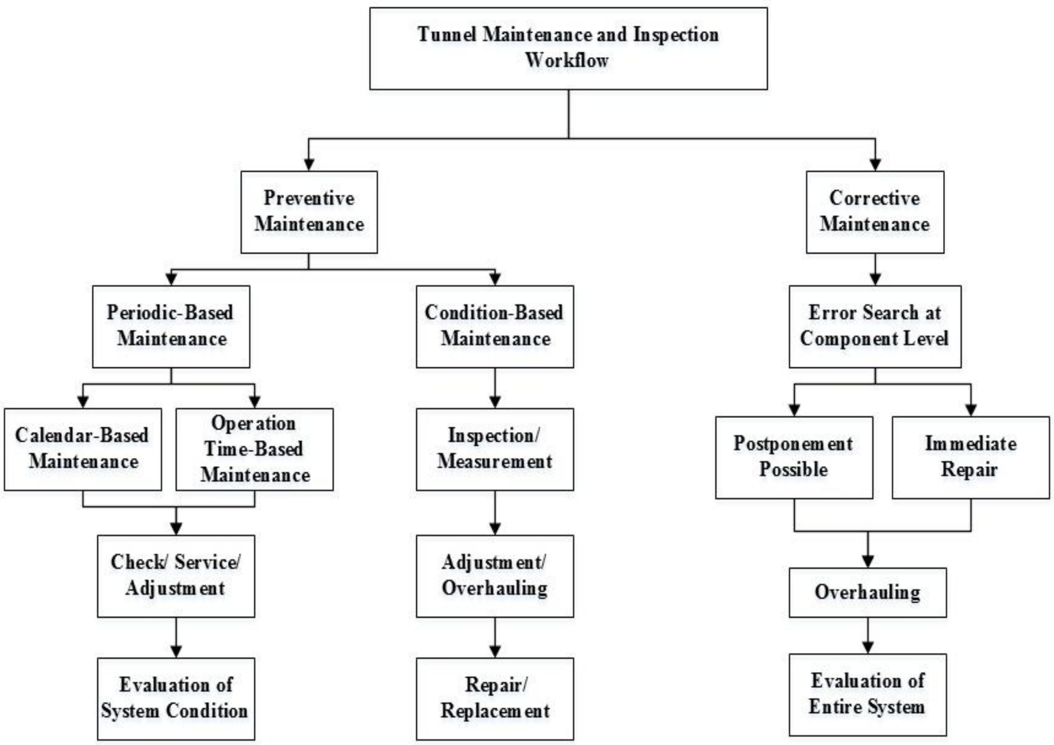


**Figure 2. PIARC Comprehensive Tunnel Maintenance and Inspection Workflow**

United Kingdom specified its asset management on eight steps including 1) setting strategies, 2) recording the assets, 3) identifying maintenance needs, 4) prioritize and management maintenance, 5) managing work programs, 6) influencing maintenance through design, 7) measuring performance, and 8) innovating and developing, and encourage all the transportation agencies to follow these steps. In addition, the comprehensive inspection plan for all the assets including tunnels and bridges includes: 1) coarse visual inspection, 2) detailed visual inspection, 3) scanner survey, and 4) machine-measured rutting system (FHWA[b], 2005).

New Zealand established its leadership to driving asset management program, not only in conceptual framework, but also in practices and daily activities for infrastructure management (IIMM, 2011).

The main elements of the New Zealand asset management plan includes: level of service and performance standard, future demand and growth, risk management, life cycle management, and plan improvement, review, and monitoring. Also, the uniqueness of this asset management plan was to address the sustainability planning and activities associated with asset management.

Nevertheless the technical and engineering aspects of asset management program development have been the main foci of transportation agencies; several studies argued the implementation of asset management is inevitable without any change on managerial and cultural behavior of the organizations (Bugas-Schramm, 2008; Cookseyet et al, 2011; Too, 2012; Brunetto et al, 2014; Shah et al, 2014). For instance,Brunetto et al.(2014) concluded that the first approach toward the asset management program was to establish the conceptual and strategic business framework for the organization. Wethyavivorn et al. (2009) determined four factors as a business managementframework to improve managerial and cultural behavior in construction organization: 1)explicit strategic management, 2)positive organizational culture, 3)excellent human resources management, and 4)efficient information technology.

## 3. Tunnel Asset Management (Tam) Framework

TAM program specifies a strategic approach to manage all aspects of tunnel assets to achieve specific objectives of asset management. Tunnel agencies should furnished their TAM program to address not only tunnel maintenance, tunnel condition assessment, and risk evaluation, but to help them reduce life cycle cost, manage risk effectively, improve the level of safety through a framework asset management program plan. Zamenian and Koo (2013) defined the conceptual TAM framework based on three main hierarchical steps of TAM application. The steps are 1) strategic plan, 2) tactical plan, and 3) operational plan as shown in Figure 3.

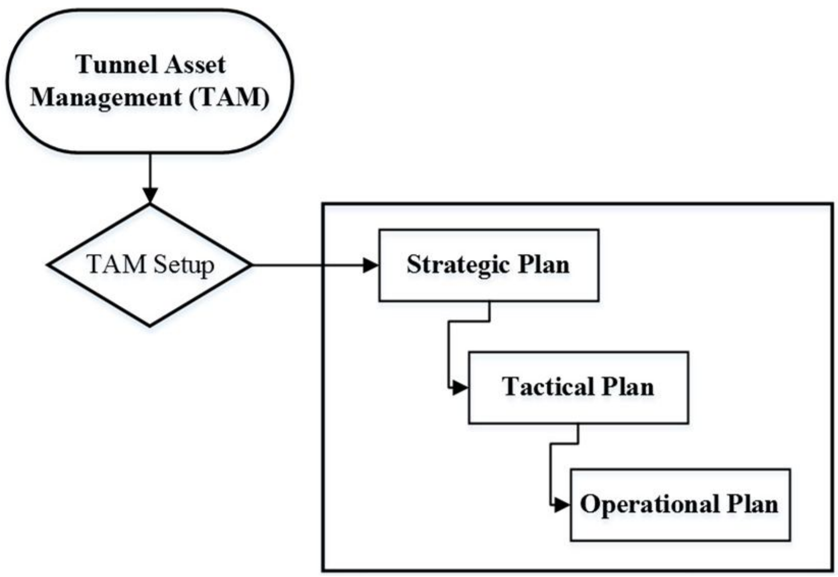


**Figure 3. Tunnel Asset Management (TAM) Framework**

### 3.1 Strategic Plan

The first step of TAM framework describes as a strategic plan. Strategic plan is to outline overall direction of the asset management. The strategic plan outline shall be guided in mission statement, goals, and objectives in broad and long term perspective. Although strategic plan of individual tunnel agency varies and only serves as agency-wide decision making,few common strategicdirections can be identified as follows: 1) financing for TAM; 2) impact of public service; 3) enhancing sustainability; 4) maintaining resiliency; and 5) long-term capital improvement plan. Thus, a strategic plan should be incorporated with the organization's business plan.

### 3.2 Tactical Plan

The second step of TAM framework is setup as a tactical plan. The tactical plan provides a meaningful translation of strategic plan into an organizational implementation. The tactical plan definesstrategic plan programs for best management practices (BMPs) to fulfill the long-term goals and objectives determined by the strategic plan. The main purpose of the tactical plan in asset management is to define tactics providing holistic directions to achieve the strategic goals and objectives determined in the strategic plan. An example of a tactical plan consists of sub-plans as shown in Figure 4.


**Figure 4: Six Sub-plans of Tactical Plan for TAM Program**

The proposed tactical plan and BMPs take account of unique characteristics of main tunnel components. This proactive approach of a tactical plan enablesthe tunnel owners to make better decisions. Goals and objectives from a strategic plan shall be impregnated to sub-plans.

### 3.3 Operational Plan

The third step of TAM framework describes as an operational plan. In order to support and implement the tactical sub-plans, specific field operational plan needs to be implemented. An operation manager develops the specific requirements and operational activities in the operational plan to accomplish objectives described by the tactical plans. For example, operational plan determines specific inspection technologies, sequences, repair methods, decision making procedures, data collection and report procedures.An example of a tactical plan consists of sub-plans as shown in Figure 5.

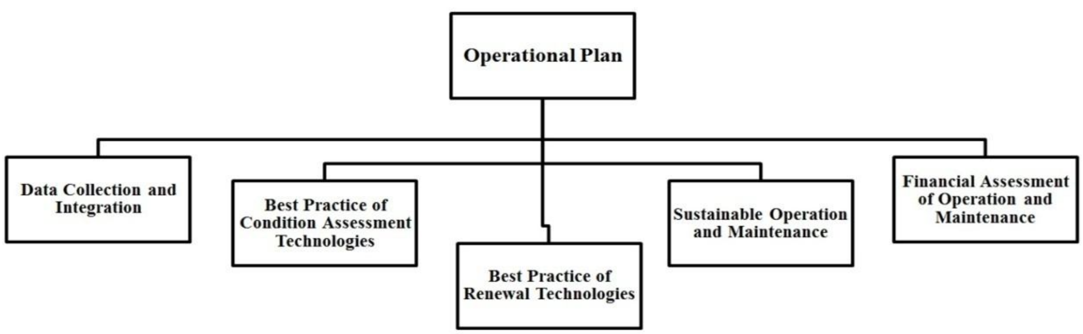


**Figure 5. Five Sub-plans of Operational Plan for TAM Program**

Accuracy of data collection and integration is a fundamental element of acondition inspection and assessment. Data collection method for TAM framework can be conducted as a manual, automated, and remote collection procedure. The level of detail for the collected data defines the data collection procedures. For instance, visual inspection is classified as a direct manual method. Laser scanning of tunnel structure is an example of automated and the fiber optic sensor for strains and displacement measuring of tunnel ceiling panel is a remote data collection method. The collected data is required to integrate in a comprehensive data for decision making. The tunnel operation manager should provide the best practices of condition assessment and renewal technologies for the inspection, maintenance, and renewal process of tunnel components followed bya tactical plan.

Application of new and emerging technologies shall be reflectedin an operational plan. By conducting the condition assessment practice, each component of tunnel will be graded from 1 to 5 as shown in Table 1. The condition assessment grading will be utilized by trained tunnel operation personnel. Sustainability shall be anelement of operational plan. Three aspects of sustainability including environmental, social, and cost shall be considered for specific sub-operational plans. Financial assessment is a process of managing capital for tunnel asset management including all inspection activities, operation & maintenance activities, and renewal. The International Infrastructure Maintenance Manual recommended considering five factors for financial assessment of operation and maintenance for an asset. These factors including: 1) initial capital investment cost, 2) operation and maintenance cost, 3) rehabilitation and repair costs, 4) administration, overheads, and taxes, and 5) depreciations (IIMM, 2011).

The effective integration and efficient streamline from strategic, tactical, to operational plan shall ensure success of TAM application. The following section is a TAM case used to ensure structural integrity of concrete ceiling panels and bolts.

## 4. Tam Application

Initial phase for TAM application to develop the tactical plan framework is to have a comprehensive asset inventory and data management system. The initial phase helps tunnel agencies collect, store, manage, and analyze data in an effective and efficient way.This phase provides an important fundamental baseline for other tactical plansand decision making process. Common data are: 1)assetlocation, 2) asset physical attributes, and 3) conditioninspection and assessment.

The second phase of tactical plan is defined as inspection and maintenance plan. The inspection and maintenance activities of tunnel components is a broad topic including tunnel structure, mechanical systems, electrical systems, drainage systems, and emergency systems. Each of these systems will be divided into small portion and required specific considerations.The inspection and maintenance plan should identifycondition inspection technologies and application procedures in order to create a baseline of long term condition assessment. For example, Sasago tunnel accident case revealed that there was no routine inspection plan and no monitoring technologies available prior to failing anchor bolts. According to Ministry of Land, Infrastructure, Transport and Tourism (MLIT) of Japan, tunnel defects were found especially where structures were suspended by metal fitting for hanging. Typical defects include anchor bolt loose, anchor bolt loss, and lining concrete cracking. Concrete ceiling panel were suspended by steel bracket and fixed with anchor bolt using chemical adhesion and physical compression. After the accident, extensive inspection revealed that more 1,600 anchor bolt related defects were found. Post-accident inspection used manual, visual and sound check inspection technique. Strain or deformation sensors were not installed in the tunnel (Kawahara et al, 2013).

One of the functions of inspection and maintenance plan is to determine the current condition of an asset as a means of prioritizing replacement and rehabilitation efforts. Condition assessment depends on the inspection plan, data interpretation, and engineering judgment. Table 1 provides condition assessment ranks for inspection assessment.

**Table 1: Condition Assessment of Tunnel**

| Rank | Condition |
|---|---|
| 1 | Very Good Condition-Regular Maintenance Required |
| 2 | Minor Defects-Specific parts needs Maintenance |
| 3 | Major Defects-Significance Maintenance Required |
| 4 | Requires Renewal-Significant Renewal required |
| 5 | Tunnel Unserviceable-Asset needs to be closed |

Some tunnel components are more important than others and asset condition is only one of the factors to make a decision on prioritizing interventions.

It is better to understand that reactive response such as “do nothing until a system component fails” is not a suitable approach due to its costly repairs, public safety concern, and environmental problems. Risk assessment not only determines the failure probability of assets, but it will also identify the consequences process of asset failure. As a part of risk assessment and prioritization plan, the business risk exposure (BRE) requires to develop in order to identify the criticality of the asset components. The BRE formulation has been defined as the product of Probability of Failure (POF) and Consequence of Failure (COF):*Business Risk Exposure (BRE) = Probability of Failure (POF) × Consequence of Failure (COF)*

Tunnel manager with consideration of strategic plan will determine the POF and COF for tunnel asset components. The POF can be assessed through history data and inspection process. The COF is characterized by such factors as the location of asset (for example crowded downtown areas versus sparsely populated areas), damage criticality, service criticality and resiliency. Then, the decision making matrix for prioritization plan will be developed. An example of such as matrix is shown in Figure 6. The Level of service, budget, and safety considerations are the typical concerns of any assets. The implementation of these three objectives in tactical plan will be explored to address the tunnel ceiling panel inspection, as a high risk structural component.

| | | Consequence of Failure (COF) | | | | |
|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 |
| Probability of Failure (POF) | 1 | Very Low | Very Low | Low | Medium | High |
| | 2 | Very Low | Low | Medium | High | High |
| | 3 | Low | Medium | High | High | Very High |
| | 4 | Medium | High | High | Very High | Very High |
| | 5 | High | High | Very High | Very High | Very High |

**Figure 6. Decision Making Matrix for Business Risk Exposure Analysis**

## 5. Inspection Technologies

Inspection of existing infrastructure components is the most critical activity among the operation plans. All tactical six sub-plans heavily depend on appropriate inspection assessment. This section discusses existing and new technologies for tunnel structural condition inspection and assessment.

Inspection and monitoring technologiesfor civil infrastructure system shall provide continuous and reliable condition information. Timely response of structural component defect is one of the crucial factors to ensure public safety. Due to advancement of information technology (IT), new technology application such as smart sensor and wireless communication networkbecome a possible option. The structural inspections for detecting strain, temperature, crack, corrosion, displacement, and inclination of infrastructure assets at the critical locations now can be monitored through IT network system.

Condition inspection for structural tunnel ceiling panels is based on measuring maximum allowable displacement or strain magnitude of structural components including panel, hanger, bracket, anchor, and bolts.

Visual inspection of measuring displacement and strain is challenging because of low accuracy and limited access to the connecting components and obstructing inspector's sight. Fiber optic sensors and digital image processing are proposed to enhance sustainability of existing tunnel systems.

Fiber optic sensors have been used for monitoring of strain and displacement in bridges structures as well as pavement structures because of its accurateness and inexpensiveness (Casas and Cruz, 2003; Ballado et al, 2004; Mehrani and Ayoub, 2006; Modares and Waksmanski, 2013).A long-gauge fiber optic sensor can be used to measure strain between two points as shown in Figure 7. Point A and B are the sensor anchoring points and the measurement of the sensor represents a displacement between them (Glisiae and Inaudi, 2007). This sensor has been applied in civil structures such as bridges for measuring the vertical displacement. The fiber optic sensors have been utilized in the London Underground tunnel to measure changes in displacement, inclination, and temperature in the 180 m long stretch of concrete-lined tunnel (Stajano et al, 2010).

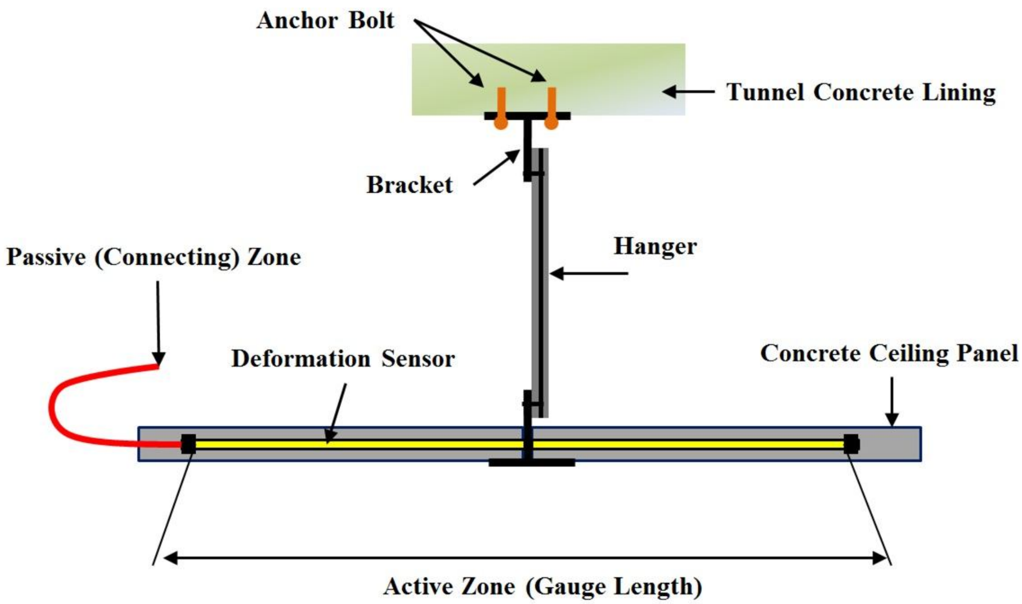


**Figure 7. Long-gauge Fiber Optic Sensor for Inspection of Tunnel Ceiling Panel**

The image processing technology has been widely used in measuring the displacement of structures in the civil field and experimental solid mechanism (Cheng et al, 2003; Lee et al, 2006). The digital image processing technology consists of three basic steps. First, a digital video camera with a telescopic lens is installed on a stable point that can monitor the ceiling panel structure. Second, the camera takes a motion picture of the ceiling panel structure at the measurement point. At this time, the displacement of a target point captured by the camera is calculated using image processing technology. Third, the image processing calculation uses the actual displacement of target geometry of ceiling panel structure and number of pixels moved (Lee and Chang, 2005).The digital image processing technology, in terms of simplicity and cost-effectiveness, is the best option for tunnel agencies to utilize for the inspection of tunnel ceiling structures. This technology can be utilized for displacement measurement by using hardware including a target object, a telescopic lens, a digital camcorder, a IEEE1394 port, and a laptop computer, and software including continuous image capturing, a target recognition algorithm, calculation of a trigonometric transformation matrix from pre-captured images, and the actual displacement calculation from on-line image data (Lee and Chang, 2005; Yoneyam et al, 2007).Figure 8 shows an example of digital image process.

The digital image processing technique is simple andcost-effective technology which can be integrated to real time monitoring system.

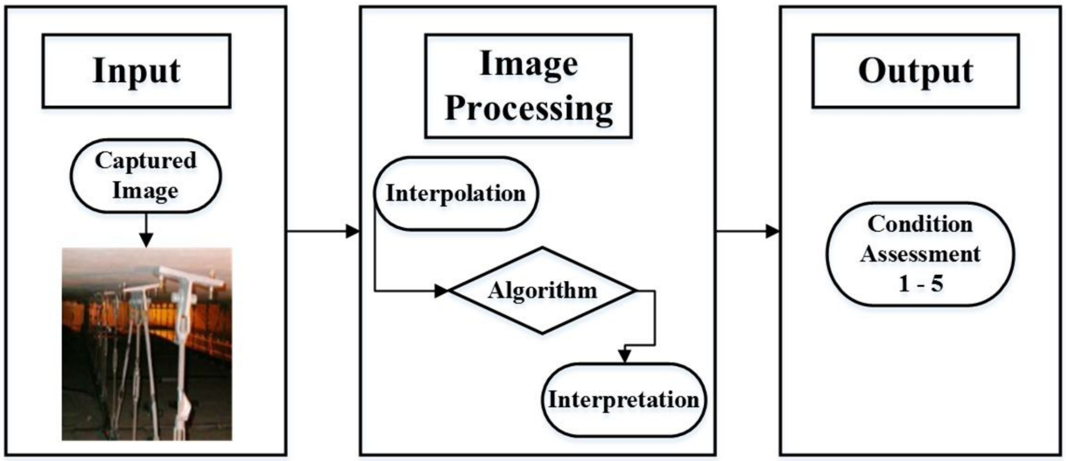


**Figure 8. Digital Image Processing for Inspection of Tunnel Ceiling Panel**

Long-gauge fiber optic sensor and digital image technologies are presented as examples of new technologies. Other technologies can be implemented for the tunnel inspection. As awareness of public safety and sustainability of tunnel systems increase, demand for TAM implementation will grow especially in development of advanced inspection technology.

## 5.0 Conclusions

This paper proposes a comprehensive Tunnel Asset Management (TAM) framework for tunnels including the advanced condition inspection technologies for structural components. Literature review revealed that transportation agencies around the world have adopted the concept of asset management; however, asset management for tunnel is not effectively integrated and organized.The proposed TAM framework consists of three main hierarchical steps: 1) strategic plan, 2) tactical plan, and 3) operational plan. The strategic plan defines the organizational goals and objectives in long-term perspective. The tactical plan identifies the specific approach to accomplish the long-term goals and objectives. The operational plan proposes specific action plansto achieve goals and objectives from the tactical plan.

The ability to continuously monitor the structural integrity of the tunnel structural component sensures public safety. However, the implementation of advanced inspection technologies for the practice for critical structural components such as tunnel ceiling panel is still in its infancy.Observing, controlling, and predicting the onset of fatal structural behavior can provide early warning allowingrepair or rehabilitation prior to incident. This paper presents two inspection technologies, fiber optic strain sensors and digital image processing, to enhance condition monitoring of existing tunnel structure systems.

The proposed two technologies have pros and cons. The digital image processing is relatively easy to install and can be cost effective.However, capturing digital image can be interrupted by surrounding conditions and process requires analysis algorithm to ensure maximum allowable deformation. The long gauge optic fiber sensor directly measures deformation of structural components. However, sensors should be embedded or firmly attached on the structural components. TAM application can be improved through continuous research and development of new technology. TAM is an essential management tool for all tunnel asset managers to protect general public from incidents and provides seamless infrastructure services.

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