

# Design and development of highway tunnel maintenance and management system

Ge Minli<sup>1</sup> Sun Lu<sup>1,2</sup>

(<sup>1</sup>School of Transportation, Southeast University, Nanjing 210096, China)

(<sup>2</sup>Department of Civil Engineering, the Catholic University of America, Washington DC 20064, USA)

**Abstract:** In order to solve the urgent problem of how to manage and sustain highway tunnels with advanced information technology with the background of the rapid development in the modern traffic, and achieve the cost-effectiveness optimal principle objectives under the premise of guaranteeing a smooth flow of traffic; a highway tunnel maintenance and management system framework and the key modules were proposed. First, the determined highway tunnel condition assessment index system was established according to the result of expert consulting forms. Secondly, the tunnel diseases, the corresponding maintenance measurements, and many-to-many relationship between diseases and maintenance measurements were introduced. Then, three kinds of 0-1 integer programming models were built according to different tunnel operators' needs in the optimization decision module. Finally, the further development and implementation of the system was prospected. The research results can provide references to tunnel researchers and managers.

**Key words:** maintenance and management system; highway tunnel; condition assessment; distress treatment; cost-benefit analysis

**doi:** 10.3969/j.issn.1003-7985.2015.01.023

Tunnels have played an important role in many situations, such as shortening the driving distance, improving speed, reducing fuel consumption, ensuring driving safety, protecting environment, and achieving good social and economic benefits. In the last decade, many tunnels were built around the world. In the western region of China, the overall length of bridges and tunnels accounts for half of the total mileage.

While tunnel maintenance and management are unable to keep pace with the rapid development of the tunnels, which brought a considerable number of accidents and po-

tential danger, such as the Kings Cross fire in London, the fire in the Mont-Blanc tunnel in France and the accident in the Tauern tunnel in Austria<sup>[1]</sup>, which caused great concern across the entire tunnel engineering field. According to statistics from 1987 to 2008, seven tunnel accidents have caused over 400 deaths<sup>[2]</sup>.

Differing from on-ground structures, the design conditions (topography, geology, underground water, etc.) of highway tunnels vary case from case<sup>[3]</sup>. Highway tunnel operation and maintenance departments manage a large number of operations and maintenance information of highway tunnels. However, the management of the highway information is still in at a relatively lagging level, which has resulted in great hindrance to tunnel management. To ensure operation safety and timely maintenance, it is essential to do research on highway tunnel maintenance and management systems.

Highway tunnel maintenance and management systems are a rational and systematic approach to organizing and carrying out all the activities related to managing a network of tunnels, which includes optimizing the selection of maintenance and improvement actions to maximize the benefits while minimizing the costs<sup>[4-5]</sup>. The overall objective of the system is maintaining highway tunnels by making the maximum use of limited human, material and financial resources reasonably, and achieves the goal of extending the tunnel's life cycle, and raising the level of service capacity.

Inspired by the pavement management system, which was first proposed in the 1970s, some countries and researchers began to do studies in the area of tunnel management and maintenance methods.

The Federal Highway Administration (FHWA) and Federal Transit Administration (FTA) developed the national tunnel management system (TMS) in 2003<sup>[6-8]</sup>. It is comprised of two manuals and an accompanying software program. Guidelines for inspecting, maintaining, and rehabilitating highway and rail transit tunnels were provided<sup>[9-10]</sup>. The accompanying software can be used by highway and transit tunnel owners to collect and manage data on tunnel components. The TMS is now used by the District Department of Transportation (DDOT) to manage seventeen tunnels. Although this TMS system serves as a platform for data collection and management for highway

**Received** 2014-07-29.

**Biographies:** Ge Minli (1985—), female graduate; Sun Lu (corresponding author), male, doctor, professor, geminli0901@gmail.com.

**Foundation items:** The US National Science Foundation (No. CMMI-0408390, CMMI-0644552), the National Natural Science Foundation of China (No. U1134206, 51250110075, 51150110478), the Western Project of Ministry of Communications of China (No. 0901005C), the Natural Science Foundation of Jiangsu Province (No. BK200910046).

**Citation:** Ge Minli, Sun Lu. Design and development of highway tunnel maintenance and management system[J]. Journal of Southeast University (English Edition), 2015, 31(1): 137 – 142. [doi: 10.3969/j.issn.1003-7985.2015.01.023]

and transit tunnels, it is not designed to be a maintenance management system.

In August, 2010, the FHWA published the Tunnel Operations Maintenance Inspection and Evaluation (TOMIE) Manual<sup>[11]</sup> to benefit highway tunnel owners throughout the United States, which promotes uniformity and consistency in how owners are operating, maintaining, inspecting and evaluating tunnels, and also provides the foundation for building tunnel maintenance and a management system.

According to Highway Tunnel Custody Manual published by the Japan Road Association, a highway tunnel disease management system was developed by Fujii in 2004<sup>[12]</sup>. But this system does not have decision-making functions on conservation measures.

Keihin Electric Express Railway Co., Ltd. (Keikyu) developed the tunnel management system (TMS)<sup>[13]</sup> in accordance with the fundamental principle of life cycle cost (LCC) for the purpose of managing maintenance work effectiveness and economy in order to meet the requirements of the tunnel management administrators of Keikyu.

An emergency management decision support system was developed for road tunnels in Spain in 2012<sup>[14]</sup>, which provides the operator with decision recommendations to deal with the emergencies in real time. This decision support system can only be a reference in building the decision support module of tunnel maintenance and a management system.

In China, the development of the tunnel management information system particularly emphasizes operation management and monitoring management, such as the Qinghai Maping tunnel integrated monitoring and operation management system<sup>[15]</sup> and the Qinling Zhongnanshan highway tunnel monitoring system<sup>[16]</sup>. Since 2009, Guangdong province has been doing research on a highway tunnel structural safety maintenance management system for Beijing-Zhuhai north highway<sup>[17-18]</sup>. However, the development structure of the tunnel management information system in China is unitary, and mainly concentrates on the monitoring of tunnel environment and mechanical and electrical equipment. There is seldom a fully functional intelligent tunnel maintenance and management system.

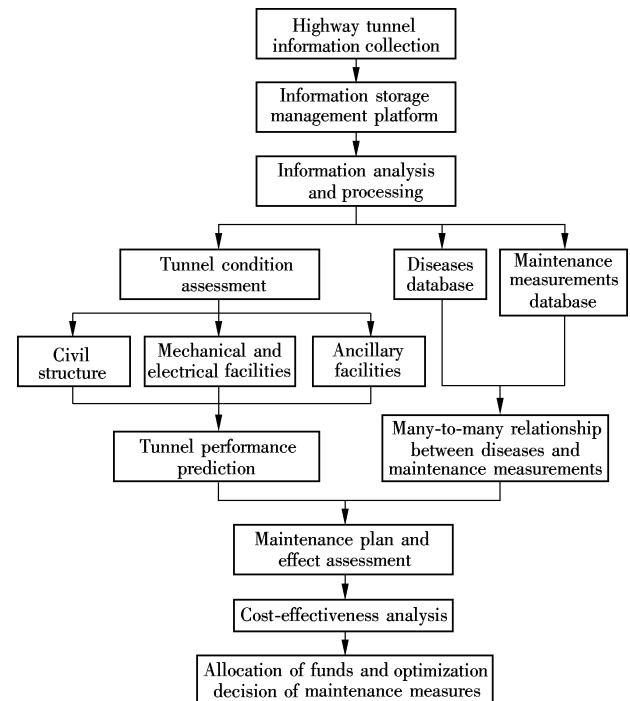
In European urban tunneling projects, the tunnel information system Kronos of Geodata<sup>[19]</sup> has been used, with the purpose of monitoring, alarming and reporting. But, it is only an information system, with no function for maintenance and decision making.

By the literature review, we can see that although the study of transportation infrastructure management, such as the pavement management system (PMS) and the bridge management system (BMS), has been continuing for more than 40 years, the development of the tunnel management system lags behind due to the difficulty of determining and diagnosing the process of deteriora-

tion<sup>[20-21]</sup>. So study on tunnel management systems is a new research field. In this study, we conducted research on the development of the maintenance and management system for highway tunnels.

## 1 System Framework and Flow Design

The highway tunnel maintenance and management system consists of seven modules: 1) Tunnel information collection; 2) Information storage and management platform; 3) Tunnel condition assessment; 4) Tunnel performance prediction; 5) Maintenance plan and effect assessment; 6) Cost-effectiveness analysis, allocation of funds; and 7) Optimization decision of maintenance measures. The detailed flow design of this system is shown in Fig. 1.



**Fig. 1** Flow design of highway tunnel maintenance and system

In this research, four system modules, highway tunnel condition assessment, disease inspection and maintenance measurements, cost-effectiveness analysis and the optimization of decisions of maintenance, will be analyzed in detail.

## 2 Highway Tunnel Condition Assessment

The content of tunnel maintenance include civil structures, mechanical and electrical facilities, ancillary facilities. The selection of evaluation indexes includes the following three aspects:

First, the preliminary evaluation index. According to the related research achievements and combined with tunnel site investigation results, the preliminary evaluation index system was established.

Secondly, index optimization. Whether the preliminary established evaluation index system is scientific and reasonable or not? 68 experts in the field of tunnel manage-

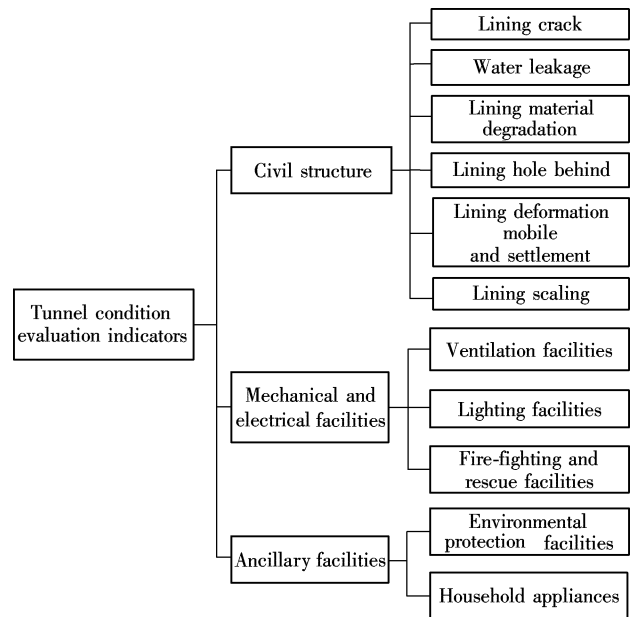
ment and operation safety were consulted by the means of interviews, phone calls and emails to complete the consulting form. The screening process included: design consulting forms, select experts, analysis consulting results, screen indexes, etc. Together we sent out 68 consulting forms and received 62 consulting forms, with the response rate of 82.3%. We modified the evaluation index according to the analysis results of the consulting results.

Finally, according to the principle of establishing an index system<sup>[22]</sup>, we amalgamated some of the index which had an inclusive relationship, and then we established the determined highway tunnel condition assessment index system, as shown in Fig. 2.

### 3 Disease Inspection and Maintenance Measurements

In this section, we introduced tunnel diseases and corresponding maintenance measurements, and many-to-many relationship between diseases and maintenance measurements.

First, all kinds of diseases and maintenance measurements were summarized and generalized; then many-to-many relationships between diseases and maintenance



**Fig. 2** Highway tunnel condition assessment index system measurements was built. So we can evaluate the effect of various conservation measures on treating diseases. Taking the civil structure as an example, the results are shown in Tab. 2 and Tab. 3.

**Tab. 2** Selection of countermeasures against tunnel diseases caused by external forces

Countermeasures	Relaxation pressure	Bias pressure	Strata landslide	Expansive soil pressure	Insufficient bearing capacity	Hydrostatic pressure	Frost force
Back grouting of lining	★	★	★	★	★	★	★
Shotcrete	○	☆		☆	☆	○	○
Anchor reinforcement	☆	★	☆	★	★	○	☆
Drainage & sealing	○	○	☆	○	○	★	★
Cover arch	○	☆	☆	☆	☆	○	○
Thermal insulation layer							★
Landslide control		☆	★				
Surrounding rock grouting	○	○				○	
Grout anchoring	☆	★	★	★	★		
Adding the inverted arch		★	☆	★	★	○	☆

Note: ★ represents the most effective method to dispose the diseases; ☆ represents a more effective method to dispose the diseases; ○ represents a less effective method to dispose the diseases. The relaxation pressure includes sudden collapse.

**Tab. 3** Selection of countermeasures against tunnel diseases caused by internal forces and others

Countermeasures	Lining material degradation	Water leakage	Others		
			Back space of lining	Insufficient thickness of lining	No invert
Back grouting of lining		○	★		
Safety net	★				
Shotcrete	☆			☆	
Anchor reinforcement	○			☆	★
Drainage & sealing		★			
Cover arch	☆			★	
Surrounding rock grouting	○	☆	☆	☆	
Grout anchoring				○	★
Adding the inverted arch					★

Notes: ★ represents the most effective method to dispose the diseases; ☆ represents a more effective method to dispose the diseases; ○ represents a less effective method to dispose the diseases. The relaxation pressure includes sudden collapse.

#### 4 Cost-Effectiveness Analysis

Various economic analysis methods are used in the infrastructure management system. According to the principles of engineering economy, this paper uses the cost-effectiveness analysis method. The cost and effectiveness are as defined as follows.

**Cost:** Considering the restriction of the maintenance fund, only maintenance and management costs are involved in this system.

$$C_{ijt} = L_i W_i c_{ijt} (1 + r)^{-t} \quad (1)$$

where  $C_{ijt}$  is the cost of adopting measurement  $j$  in the section  $i$  in year  $t$ ;  $L_i$  is the length of tunnel section  $i$ ;  $W_i$  is the width of tunnel section  $i$ ;  $c_{ijt}$  is the unit cost of adopting measurement  $j$  in the section  $i$  in year  $t$ ; and  $r$  is the discount rate.

**Effectiveness:** For a tunnel project, the better the tunnel performance, the greater the benefits. So the effectiveness can be expressed by the improvement of tunnel condition index.

$$E_{ijt} = \left[ \sum_{k=1}^n \omega_k (I_{kijt} - I_{kMit}) \right] L_i \text{AADT}_{it} \quad (2)$$

where  $E_{ijt}$  is the effect produced by the tunnel section  $i$  in year  $t$  after adopting measurement  $j$ ;  $I_{kijt}$  is value of the  $k$ -th tunnel index in section  $i$  in year  $t$  after adopting measurement  $j$ ;  $I_{kMit}$  is the minimum acceptable value of the  $k$ -th tunnel index in section  $i$  in year  $t$ ;  $\omega_k$  is the weight coefficient of the  $k$ -th tunnel index;  $L_i$  is the length of tunnel section  $i$ ;  $\text{AADT}_{it}$  is the annual average of daily traffic in tunnel section  $i$  in year  $t$ .

#### 5 Allocation of Funds and Optimization Decision of Maintenance

In the optimization decision module, many decision-making models are used, including the non-optimal decision-making method, such as the decision tree method, ranking method, and optimization decision methods, such as the mathematical programming optimization method, artificial neural network, the genetic algorithm (GA) and so on. The 0-1 integer programming method employed to build models was used in this system. The innovations are: 1) The system offers three optimizing models, from which users can choose the appropriate model according to their needs, namely targets and constraints; 2) Using the 0-1 integer programming decision model can specify and fulfill the maintenance measures for each road section; 3) The model is clarity and not complicated, and thus it is easily understood and solved.

The three decision models are as follows:

1) Minimization model of maintenance funds

$$\min f_{ijt} = \sum_i^S \sum_t^T \left\{ \sum_j^M X_{ijt} \left[ \sum_j^T L_i W_i c_{ijt} (1 + r)^{-t} \right] \right\} \quad (3)$$

s. t.

$$I_{ki(t+1)} = I_{kit} + \sum_j^M X_{ijt} \Delta I_{kj} \geq I_{kmin} \quad (4)$$

$$X_{ijt} = \begin{cases} 1 & \text{section } i \text{ takes measurement } j \text{ at year } t \\ 0 & \text{else} \end{cases} \quad i \in S, t \in T, j \in M$$

where  $I_{kmin}$  is the minimum acceptable value of the  $k$ -th index.

2) Performance maximization model

$$\max f_{ijt} = \sum_i^S \sum_t^T \left\{ \sum_j^M X_{ijt} \left[ \sum_{k=1}^n \omega_k (I_{kijt} - I_{kMit}) \right] L_i \text{AADT}_{it} \right\} \quad (5)$$

s. t.

$$\sum_i^S \sum_j^M X_{ijt} (L_i W_i c_{ijt}) \leq B_t \quad (6)$$

$$X_{ijt} = \begin{cases} 1 & \text{section } i \text{ takes measurement } j \text{ at year } t \\ 0 & \text{else} \end{cases} \quad i \in S, t \in T, j \in M$$

where  $B_t$  is the budget fund of year  $t$ , and the maintenance funds can be different every year.

3) Effectiveness-cost ratio maximization model

$$\max f_{ijt} = \sum_i^S \sum_t^T \left\{ \sum_j^M X_{ijt} \frac{\left[ \sum_{k=1}^n \omega_k (I_{kijt} - I_{kMit}) \right] L_i \text{AADT}_{it}}{\sum_j^T L_i W_i c_{ijt} (1 + r)^{-t}} \right\} \quad (7)$$

s. t.

$$\sum_i^S \sum_j^M X_{ijt} (L_i W_i c_{ijt}) \leq B_t, I_{ki(t+1)} =$$

$$I_{kit} + \sum_j^M X_{ijt} \Delta I_{kj} \geq I_{kmin}$$

$$X_{ijt} = \begin{cases} 1 & \text{section } i \text{ takes measurement } j \text{ at year } t \\ 0 & \text{else} \end{cases} \quad i \in S, t \in T, j \in M \quad (8)$$

where  $I_{kmin}$  is the minimum acceptable value of the  $k$ -th index;  $B_t$  is the budget fund of year  $t$ , and the maintenance funds can be different every year.

#### 6 Conclusions

The highway tunnel maintenance management and decision-making system is a rational and systematic approach to organizing and carrying out all the activities related to managing highway tunnels. It includes optimizing the selection of maintenance to maximize the benefits

while minimizing the costs. Through the exploration of the system, the following can be concluded:

1) On the basis of the preliminary established evaluation index system, according to the result of expert consulting forms, the determined highway tunnel condition assessment index system is established.

2) According to the cost-effectiveness analysis methods, the cost and effectiveness of highway tunnel maintenance and management are defined, which are the premises of optimization.

3) In the optimization decision module, three kinds of 0-1 integer programming models are built according to different operators' needs. Thus, selectivity is an obvious advantage of this module.

4) Accurate prediction of the highway tunnel conditions is imperative for maintenance and management, so the module of tunnel condition prediction will be added to the further development and implementation of the system.

5) With the fast development of transportation, a large and increasing number of tunnels can be considered to be a network. To ensure the safety and service performances of tunnels, not only the single highway tunnel project but also the network-level highway tunnel management requires systematic maintenance services to adjust the allocation of capital to the network-level of highway. On the basis of the project-level tunnel management, the main function of the network-level tunnel management is to maximize the efficiency of the maintenance budget within the highway network. So in future research, the network-level tunnel management and maintenance system can be built on the basis of the project-level system.

## References

- [1] Holický M, Diamantidis D. Optimization of road tunnel safety [J]. *Beton-und Stahlbetonbau*, 2008, **103** (S1): 10–15.
- [2] Carvel R, Marlin G. A history of fire incidents in tunnels: the handbook of tunnel fire safety [R]. London: Thomas Telford Publishing, 2005: 3–41.
- [3] Asakura T, Kojima Y. Tunnel maintenance in Japan [J]. *Tunnelling and Underground Space Technology*, 2003, **18** (2/3): 161–169.
- [4] Hudson W R, Haas R, Uddin W. *Infrastructure management: integrating design, construction, maintenance, rehabilitation, and renovation* [M]. New York: McGraw-Hill, 1997.
- [5] Uddin W, Haas R, Hudson W R. *Public infrastructure asset management* [M]. 2nd ed. New York: McGraw-Hill Education, 2013.
- [6] Gannett Fleming, Inc. National tunnel management system [EB/OL]. (2003) [2014-04-01]. <http://www.gf-net.com/projectdetail.asp?ProjAspect=260>.
- [7] Gannett Fleming, Inc. Best practices for implementing quality control and quality assurance for tunnel inspection [R/OL]. (2009) [2014-04-01]. [http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP20-07\(261\)\\_FR.pdf](http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP20-07(261)_FR.pdf).
- [8] Allen C, Averso M, Patrick R. Overview and implementation of tunnel management system [C]//88th Annual Meeting of the Transportation Research Board. Washington DC, USA, 2009.
- [9] Federal Highway Administration. FHWA-IF-05-002 Highway and rail transit tunnel inspection manual[S]. Washington, DC: FHWA, 2005.
- [10] Federal Highway Administration. FHWA-IF-05-017 Highway and rail transit tunnel maintenance and rehabilitation manual[S]. Washington, DC: FHWA, 2005.
- [11] Federal Highway Administration. FHWA-2008-0038-0042 Tunnel operations, maintenance, inspection and evaluation (TOMIE) manual [S]. Washington, DC: FHWA, 2013.
- [12] Fujii M, Jiang Y, Tanabashi Y. Database development for road tunnel maintenance and management by using geographical information system[C]//The 1st Joint Seminar Between Tongji University and Nagasaki University. Shanghai, China, 2004: 104–108.
- [13] Nakamura K, Ohtsu H, Takeuchi A. Development of a tunnel management system for existing railroad tunnel[J]. *Tunnelling and Underground Space Technology*, 2006, **21**: 312–313.
- [14] Alvear D, Abreu O, Cuesta A, et al. Decision support system for emergency management: road tunnels [J]. *Tunnelling and Underground Space Technology*, 2013, **34**: 13–21.
- [15] Zhao Wutai. Qinghai Mapping tunnel integrated monitoring and operation management system [J]. *Transportation Information Industry*, 2003(11): 113–115. (in Chinese)
- [16] Zhao Chaozhi, Hu Ping. Case study on operation management technology of Qinling Zhongnanshan super-long highway tunnel [J]. *Tunnel Construction*, 2010, **30**(3): 344–347, 350. (in Chinese)
- [17] Guangdong Province Highway Co., Ltd. Research and development of highway tunnel structural safety maintenance management system [J]. *Guangdong Highway Communications*, 2012(3): 152–152, 154. (in Chinese)
- [18] Lin Yigong. Research and development of highway tunnel structural safety maintenance management system [EB/OL]. (2010-08-17) [2014-04-01]. <http://jtkj.gdcd.gov.cn/net/projectprocess/detail.action?projectprocessId=1282034578921&mainType=15>.
- [19] Chmelina K, Rabensteiner K, Klaus G. A tunnel information system for the management and utilization of geo-engineering data in urban tunnel projects [J]. *Geotechnical and Geological Engineering*, 2013, **31**: 845–859.
- [20] Shahin M Y. *Pavement management for airports, roads, and parking lots* [M]. 2nd ed. New York: Springer, 2006.
- [21] Sun Lijun. *Transportation infrastructure management system: theory and practice* [M]. Beijing: China Communications Press, 2009. (in Chinese)
- [22] Dai Youhua, Guo Zhongyin, Ma Yan, et al. Safety evaluation index of driving environment of expressway tunnel [J]. *Journal of Tongji University: Natural Science*, 2010, **38**(8): 1171–1176. (in Chinese)

# 公路隧道养护管理系统的设计和开发

葛敏莉<sup>1</sup> 孙 璐<sup>1,2</sup>

(<sup>1</sup> 东南大学交通学院, 南京 210096)

(<sup>2</sup>Department of Civil Engineering, the Catholic University of America, Washington DC 20064, USA)

**摘要:**为了解决在现代交通快速发展的背景下如何利用现代化信息技术实现公路隧道养护和管理的迫切需求,且达到在保证交通顺畅的前提下实现公路隧道费用效益最优化的原则,设计了公路隧道养护管理系统的总体框架和各个模块.首先,根据专家调查和咨询,建立了公路隧道状况评价指标体系.然后,介绍了公路隧道的病害、养护措施以及病害和养护措施之间的多对多关系.根据隧道管理者的不同决策需求,提出了3种基于整数规划的决策模型.最后,展望了系统的进一步发展和实现前景.所得到的研究成果将为隧道的研究和工作提供参考.

**关键词:**养护管理系统;公路隧道;状态评估;病害处治;费用效益分析

**中图分类号:**U418