

Original Paper

The Reliability Model of Artificial Monitoring on the Anomalous Event in Expressway Tunnels and Monte Carlo Simulation

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Abstract

Artificial monitoring remains to be a major way to detect anomalous events in expressway tunnels. To estimate the reliability of artificial monitoring on anomalous events in expressway tunnels, the video surveillance and mobile inspection based reliability models of artificial monitoring on the anomalous event in the expressway tunnel were built, and Monte Carlo method was applied to calculate the probability and mean time to detect the anomalous event at the specific time. The results showed that the Monte Carlo method could simulate video surveillance and mobile inspection, and obtain the probability distribution and mean time of detecting anomalous events. The mean time to spot the anomalous event was in reverse relation with the number of inspectors, the time of mobile inspection, and the reliability probability of the monitoring pre-warning system in tunnels and was in positive relationships with the departure interval. Combined with the actual operation cost, the model serves as a basis for the artificial monitoring package.

Keywords

expressway, tunnel, anomalous event, monitoring, reliability model, Monte Carlo simulation

1. Introduction

As more and more people own a car and the expressway networks are improved in China, the number of expressway tunnels in the mountainous areas rises, ushering in increasingly convenient transportation. Meanwhile, accidents in expressway tunnels accounting for a large part of traffic accidents have a wide-ranging impact with serious consequence, extensive traffic jams and difficulty in rescue and evacuate, which causes “chain reaction”, “radiation reaction” and so forth in the neighborhood (Jia, 2009). Therefore, based on the existing equipment and safety management of expressway tunnels, it is essential to enhance the monitoring pre-warning of traffic incidents in tunnels so that they could be discovered and dealt with in the shortest time possible (Wang & Yang, 2009).

The literature studied the monitoring pre-warning system in tunnels in aspects including the construction framework (Xu, 2009; Zeng, 2008), the design plan of the monitoring system (Mohammadi, 2008; Ma, 2001; Zeng, 2004; Song, 2000), the automatic detection algorithm of the anomalous event (Liu, 1998) and so forth. Zeng Sheng et al. discussed the design of the tunnel monitoring system by categorizing the components of the system and defining the functions of the sub-systems (Zeng, 2004). Relevant studies categorized the automatic detection methods based on detection strategies, the detected cross section, and the monitoring equipment (Yan, 2006). Most studies just offered the theories of the monitoring pre-warning system in the tunnel while seldom touched its application (Xiong, 2012). However, the artificial detection method is widely applied in detecting the anomalous event, which is the core of the monitoring pre-warning system. Therefore, the artificial detection method mainly composed of a video surveillance system or artificial inspection is necessary for the safe operation of the tunnels.

In view of the above, the paper combined video surveillance in the tunnels and artificial inspection to build the reliability probability model of monitoring anomalous events in tunnels and use the Monte Carlo method for simulation. The study has theoretical significance and could be applied to popularize the monitoring pre-warning system, pinpoint its usage plan, improve the safety management of tunnel operation, and reduce traffic accidents.

2. The Reliability Model of Monitoring Anomalous Events in Tunnels

2.1 Video Surveillance Model

Surveillance cameras are usually installed in the expressway tunnel at intervals. The visual information inside the tunnel collected by several cameras is then transmitted to the monitors on the television wall in the monitor room. The whole tunnel is under around the clock surveillance without interruption by switching the real-time pictures from a few monitors.

M television surveillance cameras are installed in the tunnel in total ($i = 1, 2, 3 \dots m$), and there are a small screens on the television wall in the remote monitor room ($m > a$). The inspection frequency of a

single person to switch is λ per minute. The inspection route is shown in Figure 1. as a horizontal Z. The frequency to switch is $\frac{m \lambda}{60 a}$ per minute.

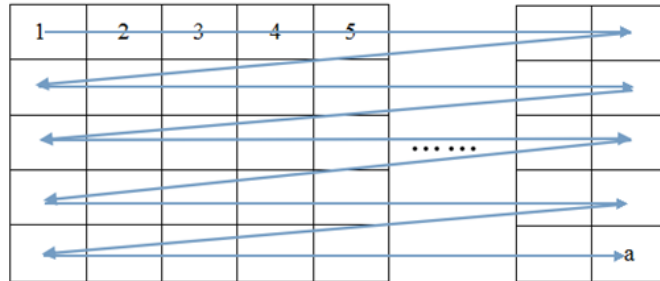


Figure 1. The Inspection Route

Assume the lens of camera n shows the anomalous event ($n \leq m$) at a specific time when the staff is inspecting screen $X \in U(1, m)$, the probability $P(Q)$ for a single person to detect it within h seconds is:

$$P(Q) = P\left\{n - \frac{h\lambda m}{60} \leq X \leq n\right\} = \int_{n - \frac{h\lambda m}{60}}^n \frac{1}{m-1} dx = \frac{h\lambda m}{60(m-1)} \tag{1}$$

For two inspectors, A inspects zone I ($i = 1, 2, 3 \dots \frac{m}{2}$) with the inspection frequency as λ_1 per minute. B inspects zone II ($i = \frac{m}{2} + 1, \frac{m}{2} + 2 \dots m$) with the inspection frequency as λ_2 per minute.

The rest conditions remain unchanged.

Assume the lens of camera n shows the anomalous event ($n \leq m$) at a specific time when inspector A and B are inspecting screen $X_1 \in U(1, \frac{m}{2})$, $X_2 \in U(\frac{m}{2} + 1, m)$. $P(A)$ and $P(B)$ are the probabilities

for the anomalous event to occur in zone I and zone II $\left[P(A)=P(B)=\frac{1}{2} \right]$ respectively. The probability $P(Q)$ for the anomalous event to be discovered within h seconds is:

$$P(Q) = P(A)P(Q | A) + P(B)P(Q | B) \tag{2}$$

Among them:
$$P(Q | A) = P\left\{n - \frac{h\lambda_1 m}{120} \leq X_1 \leq n\right\} = \int_{n - \frac{h\lambda_1 m}{120}}^n \frac{1}{\frac{m}{2} - 1} dx = \frac{h\lambda_1 m}{60(m-2)} \tag{3}$$

$$P(Q | B) = P\left\{n - \frac{h\lambda_2 m}{120} \leq X_2 \leq n\right\} = \int_{n - \frac{h\lambda_2 m}{120}}^n \frac{1}{m - (\frac{m}{2} + 1)} dx = \frac{h\lambda_2 m}{60(m-2)} \tag{4}$$

$$\text{then: } P(Q) = \frac{h(\lambda_1 + \lambda_2)m}{120(m-2)} \tag{5}$$

It could be then inferred that for k inspectors, the inspection frequencies are λ_i ($i = 1, 2, 3 \dots k$) respectively. A_i is the zone where the anomalous event takes place and the probability $P(Q)$ for the anomalous event to be discovered within h seconds is:

$$P(Q) = P(A_1)P(Q|A_1) + P(A_2)P(Q|A_2) + P(A_3)P(Q|A_3) \dots + P(A_k)P(Q|A_k) = \frac{h \sum_{i=1}^k \lambda_i m}{60k(m-k)} \tag{6}$$

2.2 Mobile Inspection Model

There are q tunnels on a certain section of the expressway ($i = 1, 2, 3 \dots q$), the staff inspect the tunnels assigned to him in the patrol car repeatedly at a frequency of μ per minute. The inspection route is shown in Figure 2.

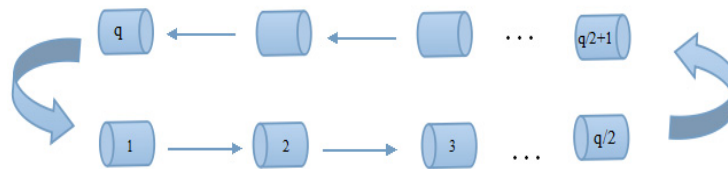


Figure 2. The Sketch Map of the Artificial Inspection Route

Assume an anomalous event occurs in tunnel n ($n \leq q$) at a specific time when tunnel $X' \in U(1, q)$ is under inspection. There is situation A and B.

Situation A: tunnel n where the anomalous event occurs is in the same direction as the inspected tunnel X' , namely

$$X' \in \left(1, \frac{q}{2}\right) \text{ or } \left(\frac{q}{2} + 1, q\right), \quad n \in \left(1, \frac{q}{2}\right) \text{ or } \left(\frac{q}{2} + 1, q\right)$$

Then the probability $P(Q)$ for the anomalous event to be spotted within h' seconds is:

$$P(Q) = \left\{ n - \frac{h' \mu q}{60} \leq X' \leq n \right\} = \frac{h' \mu q}{60(q-1)} \tag{7}$$

Situation B: tunnel n where the anomalous event occurs is in the opposite direction as the inspected tunnel X' , and the patrol car needs to turn around. This takes Δt seconds, namely:

$$X' \in \left[1, \frac{q}{2}\right], n \in \left[\frac{q}{2} + 1, q\right] \quad \text{or} \quad X' \in \left[\frac{q}{2} + 1, q\right], n \in \left[1, \frac{q}{2}\right]$$

Then the probability $P(Q)$ for the anomalous event to be spotted within h' seconds is:

$$P(Q) = \left\{ n - \frac{h' \mu q - \Delta t \mu q}{60} \leq X' \leq n \right\} = \frac{(h' - \Delta t) \mu q}{60(q-1)} \tag{8}$$

3. Monte Carlo Simulation

3.1 Simulation Objective

Monte Carlo simulation is a calculation method based on the random number. The method estimates and counts the parameters by generating time sequences repeatedly in random settings to study its distribution characteristics.

Based on Monte Carlo simulation, the Matlab platform was chosen. Simulations were made according to the reliability probability models of closed-circuit television and artificial inspection monitoring to predict the shortest time for the anomalous event to be spotted once it occurred in the tunnel and obtain the probability distribution for it to be spotted within the required time.

3.2 The Simulation

Take the video monitoring pre-warning system as an example to illustrate the simulation. Create random number A and B for the screen number showing the anomalous event and the one to be inspected respectively. The time matrix for the anomalous event to be spotted under different screen combinations was obtained after the inspection simulation by programming. The frequencies for the anomalous event to be spotted at different time intervals were counted for the probability distribution and the expected time, namely, the mean time to spot the anomalous event. The simulation is shown in Figure 3.

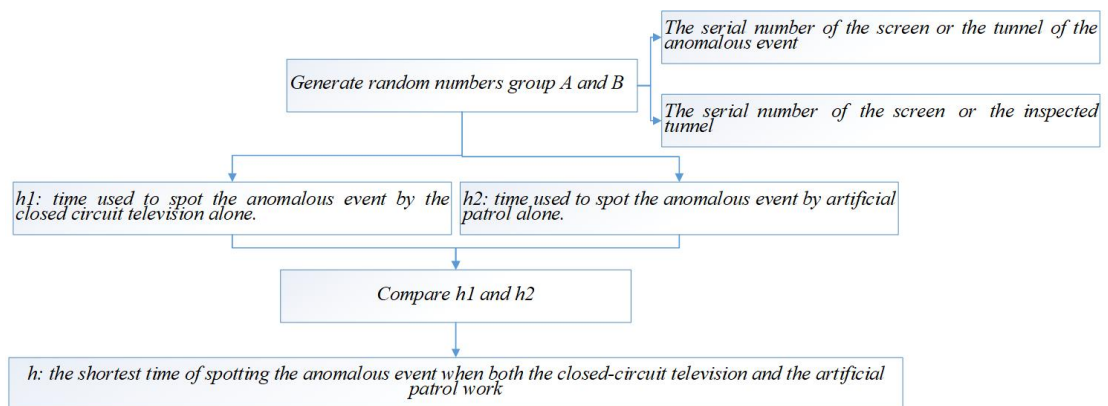


Figure 3. The Simulation Process

4. Case Study

4.1 Background

The road is 40.1km with 36 tunnels where 84 cameras are installed. Among them, a camera is installed every 125m in a tunnel on average. There are 48 monitors on the television wall in the monitor center. All the pictures are inspected by switching.

4.2 Video Monitor Simulation

It takes 5s for one staff to inspect a picture and the frequency is $\frac{1}{7}$ per minute. The frequencies for two staffs are the same and each is $\frac{2}{7}$ per minute. For several staffs ($i = 1, 2, 3 \dots k$), the frequency is $\frac{k}{7}$ per minute for each. The above formulas lead to the probability curve for different numbers of inspectors to spot the anomalous event at different inspection times, as shown in Figure 4. When one staff inspects for 7 minutes, the probability to spot the anomalous event is 100%, namely, the anomalous event is sure to be spotted within 7 minutes. For two inspectors, the anomalous event is sure to be spotted within 3.5 minutes. The probability to spot the anomalous event rises with the inspection time and the number of inspectors. However, for the safe management of the tunnel, 1-4 inspectors are necessary. A working plan is proposed based on the practical situation while taking economic costs such as the salary for the inspectors into consideration.

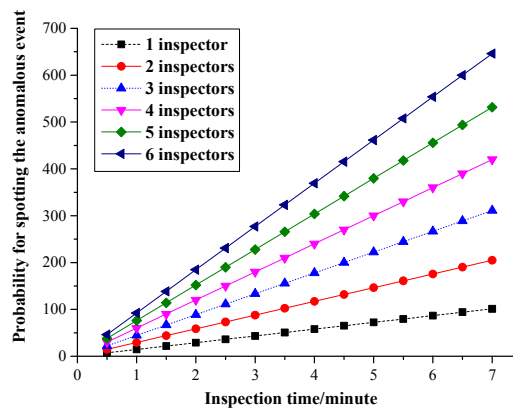


Figure 4. Probability Curve for Spotting the Anomalous Event

Simulate the screen inspection by 1-4 staffs, respectively. Divide 7 minutes, the longest time to spot the anomalous event, by 0.5 minutes to obtain the time distribution sequence to spot the anomalous event in tunnels and the weighted expected value. Table 1 shows the time distribution sequence for one inspector to spot the anomalous event. Data show for one inspector in video surveillance, the mean

time for him to spot the anomaly is
$$Et = \sum_{i=1}^{14} \bar{t}_i * P_i = 3.04 \text{ minute.}$$

Table 1. The Time Distribution Sequence for One Inspector to Spot the Tunnel Anomaly

t/min	0<t1<=0.5	0.5<t2<=1	1<t3<=1.5	1.5<t4<=2	2<t5<=2.5	2.5<t6<=3	3<t7<=3.5
P_i	8/84	5/84	6/84	13/84	8/84	4/84	8/84
t/min	3.5<t8<=4	4<t9<=4.5	4.5<t10<=5	5<t11<=5.5	5.5<t12<=6	6<t13<=6.5	6.5<t14<=7
P_i	5/84	4/84	9/84	3/84	0/84	8/84	3/84

The time and location for the anomalous event to occur are random. Two monitoring personnel inspect 84 pictures in total, and each inspects 42 pictures. Thus the mean time for the anomalous event to be spotted is 1.67 minutes. Figure 5 shows the time distribution sequence and expectation for 2 inspectors to spot the anomalous event.

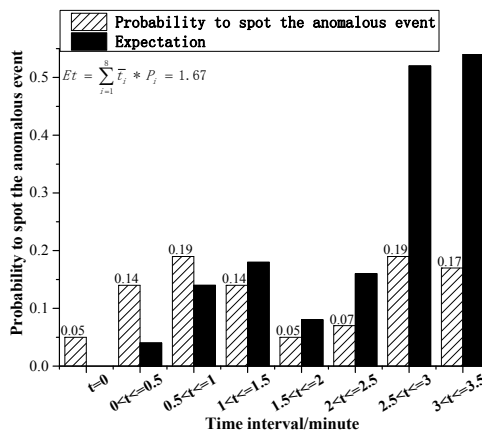


Figure 5. The Probability Distribution for 2 Inspectors to Spot the Tunnel Anomaly

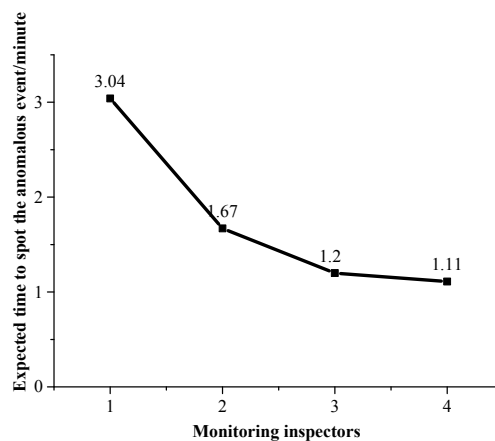


Figure 6. The Expected Time of the Anomaly to Be Spotted by Different Inspectors

Figure 6 shows the expected time for 1-4 inspectors to spot the anomalous event in video surveillance. When the number of inspectors increases from 1 to 2, the expected value of time will drop from 3.04 minutes to 1.67 minutes. When the number of inspectors increases from 2 to 3 or 4, the expected time will fall slowly. Therefore, it is necessary to increase the number of monitoring personnel from 1 to 2 under the assumption, and the actual cost should be considered for personnel enlargement.

4.3 Mobile Inspection Simulation

There are 36 tunnels for inspection in total. When the patrol car is dispatched every 1 hour to every 6h, the daily inspection ranges from 4 to 24, and the inspection frequency ranges from $\frac{1}{360}$ per minute to

$\frac{1}{60}$ per minute. Thus probability curves to spot the anomalous event for different departure

frequencies at different inspection times are calculated, as shown in Figure 7. It is sure to spot the anomalous event within 6 hours when the inspection takes place every 6 hours. It is certain to spot the anomalous event within 1 hour when the tunnels are inspected every hour. It is obvious that the probability to spot the tunnel anomaly at short time increases as the departure interval shortens and the inspection frequency increases.

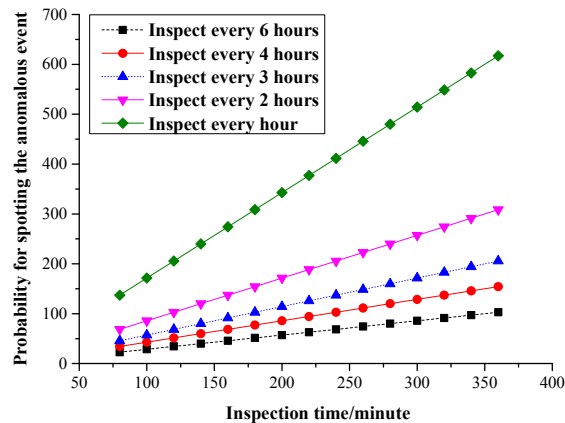


Figure 7. The Probability Curve to Spot the Anomalous Event

Similarly, simulate the artificial inspection in different plans. When the tunnels are inspected every hour, 36 tunnels are to be inspected since the anomalous event occurs at random time and location. Table 2 shows the time distribution frequency to spot the anomalous event. Thus the mean time for the spot the anomalous event to be spotted is 28.19 minutes.

Table 2. The Time Distribution Sequence to Spot the Tunnel Anomaly When the Tunnels Are Inspected Every Hour

t/min	$t1=0$	$0<t2\leq 10$	$10<t3\leq 20$	$20<t4\leq 30$	$30<t5\leq 40$	$40<t6\leq 50$	$50<t7\leq 60$
P_i	1/36	2/9	1/9	7/36	5/36	1/9	7/36

Figure 8 shows the expected time to spot the anomalous event in the artificial inspection. The probability to spot the tunnel anomaly at short time increases as the number of daily inspection increases and the departure interval shortens. Meanwhile, the operation cost of the tunnels increases accordingly. Further adjustment should be made based on the actual distance, the turn round time for the patrol car, and the cost.

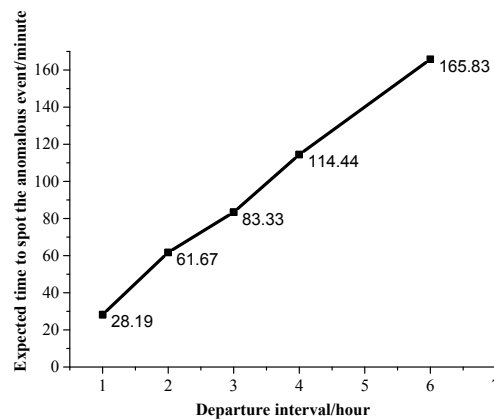


Figure 8. The Expected Time to Spot the Anomaly at Different Departure Intervals

5. Conclusions

The paper systematically studied the reliability of the monitoring pre-warning system in expressway tunnels. The probability models of the reliability for closed-circuit television and artificial inspection were established respectively. The Monte Carlo simulation method was applied to obtain the final simulation results. The main conclusions were as follows.

The probability model could judge the probabilities to spot the anomalous event in the tunnel on the same road in different monitoring plans. The simulation results lead to the probability distribution and the mean time to spot the anomalous event.

In the video surveillance pre-warning system, the probability to spot the anomalous event increases with the inspection time, and the number of inspectors. In the artificial monitoring pre-warning system, the probability to spot the tunnel anomaly at short time increases as the departure interval shortens and the inspection frequency increases.

The mean time to spot the anomalous event serves as a major index to assess the monitoring pre-warning system. Therefore, if possible, the tunnel administration could adjust the monitoring plan

appropriately so that the anomalous event in the tunnel could be spotted as soon as possible, guaranteeing the cost-saving, safe operation of the tunnels.

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References

- Deng, M. (2008, March). *Application of Highway Tunnel Event Detection*. Chang'an University.
- Han, Z., & Peng, J. G. (2006). Research on abnormal classification and warning technology of Xuefengshan super-long highway tunnel. *Zhongnan Highway Project*, 2006(31), 76-79.
- Highway Series Editorial Committee. (1999). *Highway Operation Management*. Beijing: People's Transportation Publishing House.
- Jia, W. (2009). *Study on Safety Evaluation of Expressway Tunnels*. Chang'an University.
- Liu, W. M. (1998). *Highway System Control Method*. People's Publishing House.
- Ma, Y. (2001). Scheme comparison of video surveillance in highway tunnels. *New Technologies and Products in China*, 2001(9), 81.
- Mohammadi, A. (2007). Brief Talk on the Design of Highway Tunnel Monitoring System. *Railway Survey and Design*, 2007(5), 16-19.
- Song, Y. H. (2000). Scheme design of highway tunnel monitoring system. *Northeast Highway*, 23(3), 80-83.
- Tian, X. W. (2007). *Highway Monitoring Strategy and System Design*. Hefei University of Technology.
- Wang, C., & She, L. (2004). Study on the mechanism and early warning management system of highway traffic disasters. *Journal of Wuhan University of Technology (Social Science Edition)*, 17(3), 320-323.
- Wang, Y. S. (2005). Highway Video Surveillance Networking Scheme. *China's Transportation Information Industry*, 5, 62-64.
- Wang, Z. W., & Yang, C. (2009). Current situation and development of expressway tunnel monitoring system. *Modern Tunnel Development*, 2009(6), 8-16.
- Xiong, F. (2012, June). *Comprehensive monitoring and early warning model and system for tunnel safety*. Beijing Jiaotong University.
- Xu, X. Q. (2009). *Research on Highway Traffic Accident Early Warning System*. Xi'an: Chang'an University.

- Yan, Y. (2006, April). *Algorithmic Research and Implementation of Highway Tunnel Monitoring System*. Chongqing University.
- Zeng, X. P. (2008). *Research on Theory and Method of Traffic Safety Early Warning for Highway Tunnels*. Chongqing: Chongqing Jiaotong University.
- Zeng, S. (2004). Design and Development of Highway Tunnel Monitoring System. *Modern Tunnel Technology*, 2004(41), 18-21.