Modeling and Optimization of Traffic Sensor Layout Based on Landslide Risk

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Abstract. The layout of traffic sensor network nodes is related to the economic benefits of intelligent transportation systems. In this paper, we use the information model of landslide hazard susceptibility as the new measurement method, and adapt the landslide disaster susceptibility zoning result as the constraint condition of the maximum comprehensive value optimization model. The relevant parameters of the model are analysed, and the mathematics of each parameter is given. Through the example of sensor layout of Chongqing Yuxiang Expressway, it is determined that the number of optimal section sensors is 142 and the optimal layout spacing is about 676m. The results show that compared with the widely used graph theory model, the model can not only determine the optimal number of sensors but also give the best position of each sensor. The parameters of the model are calibrated for different situations. The results show that the model is easy to extend to different cities, different road conditions and different sensor types, and has good universality.

1. Introduction

As a necessary means of collecting intelligent transportation systems (ITS), traffic sensors are receiving more and more attention. ITS requires real-time road network traffic information, and traffic sensors play an important role in obtaining real-time traffic information. Intensive deployment of traffic sensors in the road network can obtain relatively complete road network traffic information, but because of the game between cost and utility, the density of sensors is limited. Therefore, the optimization of traffic sensors is an important research direction of the intelligent transportation system. In 2008, W.L. Leow of the United States aimed at the total cost (sensor cost and congestion cost), and used the sampling theory to give the sensor layout optimization method for the expressway[1]. The paper uses the field data to treat the traffic information as a two-dimensional random signal. Using the Shannon sampling theorem, the relationship between the standard root mean square error (NMSE) and the sensor placement distance d is derived from the power spectral density. In 2017, Zhang Hongyu et al. [2] optimized the placement of the detector based on the road network unit in consideration of the layout position of the detector, considering the distribution of the detector on the road segment. Luo Jiarong[3] discussed the problem of standardization of highway monitoring facilities layout from three aspects: the vehicle detector layout method, variable information board layout method, and camera layout method.
Some scholars have done some work in the optimization of traffic sensor layout and proposed a variety of theoretical methods and models to determine the optimal number of sensors and layout[4-7]. These methods conclude two major categories: (1) sensor layout optimization method for traffic flow estimation; and (2) sensor layout optimization method for speed (or travel time) estimation. The first category is mainly applied to the traffic OD estimation, the fast road bottleneck discrimination, and the traffic flow allocation; the second category is applied to the travel time estimation and path induction based on the shortest time. However, the traditional traffic sensor layout optimization model has many shortcomings: firstly, many models are assumed to be too large to reflect the actual application requirements and the influence of specific factors, especially the graph theory-based method, and the optimization results only give the minimum edge set of the road network. The specific layout position of the sensor (front end, middle, rear end, or other position of the edge) cannot be obtained. Secondly, layout optimization is not performed according to the weight of each position in the road network, due to different positions of intersections, entrances, bridges, and sections. Traffic flow characteristics are different and need to be treated differently. Thirdly, these models cannot give the difference in sensor density on a single road segment (a directed edge in graph theory). With the continuous advancement of sensor technology, the cost is continuously reduced, and sensors are arranged in multiple sections of a single section. The optimized model is required to give an optimal density reference at different positions.

In order to overcome the shortcomings of the existing models, this paper adopts the universal traffic sensor layout optimization model considering multiple influencing factors, the maximum comprehensive value model, to study the influence of different layout density on the comprehensive value. The model considers environmental factors, road factors and sensory factors that affect sensor layout, and considers different landslide risk levels (high sensitive area, medium sensitive area, low sensitive area, polar sensitive area), different road grades (fast road, highway, Urban trunk roads, branch roads, etc.), different layout locations (crossroad sections, terrain dangerous road sections, accident-prone road sections and tunnel entrances and exits) and different sensor types (coils, video, microwave, geomagnetism, etc.). These factors are embodied in the model parameters.

2. Information Quantity Method Model for Landslide Disaster Susceptibility Evaluation
The information method is a kind of statistical method. Based on information theory, it is considered that the probability of occurrence of an event is related to the quantity and quality of information obtained during the event analysis. In the evaluation of geological disasters, the information quantity method is used to evaluate the various influencing factors of geological disasters, and the close relationship between them and the geological disasters is determined according to the magnitude of the information obtained by each factor. Because landslides are caused by many factors, each factor plays a different role in the occurrence of landslides. Therefore, when studying landslide disasters, it is not only considering one factor but considering various factors that cause landslide disasters. Therefore, the different value ranges of each influencing factor are the results of the interaction. The amount of information is calculated as shown in Equation 1.

\[
I(Y, X_1X_2X_3...X_n) = \ln \frac{P(Y|X_1X_2X_3...X_n)}{P(Y)}
\]

In formula (1), I(Y, X_1X_2X_3...X_n) is the amount of information provided by the factor X_1X_2X_3...X_n for landslide hazards at different stages of value; P(Y|X_1X_2X_3...X_n) is the probability that the landslide occurs when the factor X_1X_2X_3...X_n takes different range values; P(Y) is the probability of landslide occurrence. The combination of different influencing factors can provide positive or negative information for the landslide. When P(Y|X_1X_2X_3...X_n) > P(Y), it indicates that the combination of different factors is favourable for predicting the landslide. When it is less than zero, it indicates that this combination is not conducive to the occurrence of the landslide.
3. Maximum comprehensive value optimization model

This paper mainly discusses the layout optimization of sensors from a macro level. At the micro level, we considered the specific characteristics of the detector, and analysed different types of sensor selection problems in different situations. At the macro level, we considered the traffic characteristics of road sections and road networks. The traffic flow state parameters are obtained through data detection and data fusion, and the sensor layout problems under different applications and different road sections are analysed. The regional sensor layout optimization problem can be transformed into sensor layout optimization problems for multiple road segments. The weights of different locations within the road segment (road segments, intersections, bridge regions, etc.) are reflected by the model parameters. The modelling goal of this paper is to lay out the appropriate number of sensors in the appropriate position of the research section to maximize the comprehensive value of the road section. The comprehensive value here is the difference between the information value and the comprehensive cost of all traffic sensors deployed on the road section.

3.1. Model representation

Firstly, the position of the first and the last two sensors which must be laid on the research section is determined, and the length L (the distance between the first and the last sensors) of the research section is obtained. Secondly, n positions are evenly densely selected as the candidate placement points (including the positions of the first and the last two sensors) and the positions of the sensors are numbered as \( i \) \((i = 1, 2, \ldots, n)\), the location of the first sensor is the origin of coordinates, and the maximum comprehensive value model can be established as follows:

Max \( Z = \text{Total information value} - \text{Total cost} = I_1 + \sum_{i=2}^{n-1} I_i + I_n - \sum_{i=1}^{n} X_i C(i) \) (2)

constraint condition:

\[
\begin{align*}
I_i &= X_i q(i) V(i) \left( \frac{\int_{x_{i-1}}^{x_i} f_i(x) dx}{\int_{x_{i-1}}^{x_{i+1}} f_i(x) dx} \right) \\
X_i &= (i-1)d \\
d &= \frac{L}{(n-1)} \\
X_i &= 0 \text{ or } 1
\end{align*}
\] (3)

Where \( Z \) is the comprehensive value, i.e. the information value of all the sensors in the study section in their life cycle minus their comprehensive cost; \( I_i \) is the equivalent value of sensor \( i \) in this life cycle; \( q(i) \) is used to detect the accuracy of traffic information in the life cycle; \( V(i) \) is the information value of sensor \( I \) in the life cycle; \( C(i) \) is the comprehensive cost of sensors in life cycle; \( X_i \) is the location coordinates of sensor \( i \), and \( x_{i+1} - x_i = D \) (D is the distance between two candidate points); \( f_i \) is the information degree function of the \( i \) location of the sensor; \( X_i = 0 \) or 1 indicates the candidate layout position sensor \( i \), 0 on the contrary; \( a_i, a_i+1 \) are the coordinates of the information function \( f_i \) and \( f_i, f_i+1 \) superposition points respectively. Since sensors 1 and \( n \) are respectively located at the two ends of the research section, so \( a_1 = 0, a_{n+1} = L \); \( f_i \) and \( f_i+1 \) are the information function corresponding to the position \( i(X_i = 1) \) on the left side of position \( i \) and the adjacent position \( i(X_i = 1) \) on the right side when \( X_i = 1 \) respectively.

3.2. Case solving and result analysis

(1) Information Quantity Method Model

Using Arcgis software and the information volume model described above, based on the layer data of the landslide and the prepared impact factor layer data, we calculate the information value of each sub-class of each impact factor to the landslide occurrence and obtain the information volume distribution map of each impact factor selected.

(2) The overall cost of the sensor

Chongqing Yuxiang Expressway is a two-way four-lane road, where the number of lanes in a one-way section is 2. Reference [8], the price of a single sensor node for each lane is 1000 yuan, the cost of laying is 1000 yuan, and the annual maintenance cost is 500 yuan. The comprehensive cost of each
unidirectional section is: \[ C = C(i) + C_d(i) + T(i)C_m(i) = 2 \times 1,000 + 2 \times 1,000 + 2 \times 6 \times 500 = 10 \, 000 \] yuan.

(3) Sensor information value

According to the relevant literature, the sensor's service life is 6 years, and the annual calculation is 365 days. The congestion cost per car per hour is 8 yuan, the external cost is 2 yuan, and the four peaks are crowded every day. Besides, it is assumed that the number of average crowded vehicles reduced by any sensor at any position on the road segment is 170 per hour. That is: \( T_1 = 6, T_y = 365, T_p = 4, C_e = 8, C_s = 2, Q_d = 170. \) Then the information value of each sensor is: \[ V = \frac{T_1}{T_y} \frac{T_p}{T_p} (C_e + C_s) Q_d = 6 \times 365 \times 4 \times (8 + 2) \times 170 = 14892000 \] yuan.

(4) Sensor accuracy

According to the literature \([9-10]\), the accuracy of the traffic flow detection of geomagnetic sensors is \( q = 95\% \).

(5) Instance solution

According to the calibration result of each parameter of the simplified model, the total synthetic value \( Z(n) \) is a single independent variable function about the number of sensors \( n \). When the total synthetic value is maximum, the optimal number of sensors is 72, and the maximum synthetic value is \( 5.12 \times 10^7 \) yuan. The number of points for the one-way optimal detection section of Chongqing Xiaoxiang Expressway is 142, and the number of nodes required for geomagnetic sensors is \( 142 \times 2 \) (average number of lanes) = 284. The optimal detection section layout spacing is \( d = 48/(72-1) = 0.676 \) km; when a layout point is selected as the origin, the optimal layout point position coordinates can be obtained. \( X = (i-1) d = 0.676(i - 1) \), where \( i = 1, 2, \ldots, 72. \)

4. Conclusions

(1) By analysing the problem of traffic sensor layout, the sensor layout optimization model for highways—the maximum comprehensive value optimization model is established, and the parameters of each model are calibrated. In order to facilitate the model solving, the simplified model given in the paper can be applied to the sensor layout optimization of the actual road, and the form is simple, which is easy to obtain the optimal solution. It provides a basis for practical engineering application and has certain reference value.

(2) The maximum comprehensive value model in this paper can give the optimization results, and get the optimal detection section layout spacing and optimal position. By calibrating the model parameters of different cities, different road grades, different sensor types and different traffic information types, the sensor layout optimization results under various parameters can be obtained, which indicates that the model has good universality.

(3) Through the example of sensor layout of Chongqing Xiaoxiang Expressway, it is determined that the number of optimal section sensors is 142 and the optimal layout spacing is about 676m. The results show that compared with the widely used graph theory model, the model can not only determine the optimal number of sensors but also give the best position of each sensor. The parameters of the model are calibrated for different situations.

Acknowledgments

This work was financially supported by The National Key Research and Development Program of China(2017YFC0803900) and the China Transport Telecommunication & Information Center reserve project in 2017 (2017CB05).

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