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Speed Limit Optimization of Expressway Based on Risk Factors Model

Jun Gong

School of Traffic & Transportation, Chongqing Jiaotong University, Chongqing 400074, China;

603140371@qq.com

Abstract

To make the speed limit of expressway more reasonable and the overall risk of highway within an acceptable range, taking Chongqing Hechang Expressway （K24+680m-K74+780m）as an example, the work flow of risk factor analysis method is proposed, and then the risk factor analysis model and MATLAB are used to optimize the solution. The better speed limit scheme of highway risk in the acceptable range is obtained. The results show that the risk factor analysis method has a good control effect on the risk of road accidents, and the optimized speed limit scheme can significantly reduce the risk level of roads.

Keywords

Risk factor analysis; Speed Limit; Expressway; Traffic engineering.

1. Introduction

According to statistics, the number of deaths per 100km of motorway traffic accidents in all countries is more than that of ordinary roads of the same length, and the absolute value of the difference between the two in our country is even greater, up to more than 10 people [1]. Overtaking is a major cause of traffic accidents, and studies have shown that when drivers drive on highways, more than half of the proportion of drivers tend to overtake, and the number of traffic accident fatalities due to speeding accounts for more than 10% of the total number of deaths each year [2]. Speeding leads to deterioration of vehicle driving stability, exacerbates the longitudinal interference between vehicles, and significantly increases the chance of accidents [3]. Therefore, speed management on motorways is a necessary tool to improve operational safety.

The commonly used methods for determining the speed limit of highways in China mainly include the speed limit method based on design speed, the speed limit method based on operating speed and the speed limit method based on accident risk [4]. The development history of speed limit on highways in China shows that the speed limit method based on design speed has many defects, which is easy to cause a large difference between the speed limit value of the highway and the driver's desired speed, which affects driving safety and causes a waste of resources. The speed limit method based on operating speed is relatively better than the former, but it does not deeply consider the occurrence of traffic accidents, roadside environment, linear conditions and sight distance, etc., and the risk of traffic accidents is high and not at an acceptable level. In response to the above problems, the Ministry of Transportation carried out research on speed limit evaluation standards, and on 28 June 2020, it issued the implementation announcement of JTG/T 3381-02-2020 "Design Specification for Highway Speed Limit Signs", which put forward the risk factor argumentation method [5]. The method takes into account the likelihood and severity of accidents, and the speed limit value of a road is determined by the risks associated with the technical indicators of the road, operational characteristics, roadside interference, and the environment along the road, so that the overall risk of accidents when a vehicle is travelling according to the speed limit value is within an acceptable range. In this paper, the method will be used to demonstrate the optimisation of speed limit and control of risk on Hechang Expressway (K24+680m-K74+780m) in Chongqing Municipality.

2. Risk factor analysis methodology and implementation process

Risk factor analysis method is to divide the mileage of the highway project into multiple speed limit argumentation units according to the kilometre homogeneity index, and then according to the principle of dividing the speed limit section, divide the highway project into one or more speed limit sections, and then according to the actual situation, appropriately reduce the speed limit value of high-risk sections and locally increase the speed limit value of the low-risk sections, and adjust the speed limit value according to the multiplier of 10km/h, and take safety improvement measures. At the same time, it should take into account that the speed difference between adjacent speed-limit sections should be no more than 20km/h, and finally get the speed-limit programme that makes the proportion of the overall high-risk sections close to 30% (the overall acceptable range of accident risk), and the left and right lines of the motorway should be demonstrated separately.

2.1. Division of argumentation units

Before using the road risk factor analysis model for speed limit argumentation, the road is divided into argumentation units, which can be divided according to 100m as the standard average, or according to the same nature of the road's geometric alignment, roadside interference and the environment along the road, etc., but the length of the argumentation unit should not exceed 1km.

2.2. Classification of Speed Limit Roads

A road project can be divided into one or more general speed-limit sections according to the trend of significant changes in the road's functional positioning, technical indicators, roadside interference and the environment along the road. A general speed limit section should contain a number of special speed limit sections, including kilometres of technically restricted sections, extra-long tunnels, short tunnels (less than 2km), special bridges and other sections, interchanges, service areas and other sections, and road-side interference and accident-prone sections. The demarcation point of general speed-limit sections should be located at the point where the functional positioning of the highway has changed, the technical indicators have changed, the roadside interference situation has changed and the environment has changed significantly.

2.3. Road risk factor analysis model

The road risk factor analysis model classifies road risks into five categories based on the type of road traffic accident, and the value of each category of risk consists of the likelihood of the accident type occurring, its severity, and the corresponding operating speed and traffic volume. Among them, the indicators of off-road risk (R_1) are selected according to the influencing factors of roadside accidents and the severity of roadside accidents [6]; the indicators of frontal collision risk (R_2) caused by loss of vehicle control are oriented to the continuous long and steep downhill sections of highways; frontal collision risk (R_3) caused by vehicle overtaking provides reasonable control of the three decomposition processes of overtaking behaviours; and intersection Risk (R_4) is mainly for highway interchanges and service area ramps to separate the merging area; Risk of access (R_5) is mainly oriented to the building complexes along the graded highway, the object of study in this paper is the closed operation of the highway, there is no external access, so R_5 = 0.

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$$\mathrm{HR} = \sum_{n=1}^{5} \prod_{i=1}^{4} \prod_{j=1}^{m} R_{nij} \tag{1}$$

In the formula, R_n is the number of risk types of road risk HR, R_{ni} is that there are i types of risk components in the nth risk type, and R_{nij} is that there are m risk influencing factors under the i type of risk components in the nth risk type.

2.4. Data standardisation

Since the data of speed, radius of flat curve, lighting, and the setting of signs and markings of the road are not unified in terms of the unit of measurement, it is necessary to normalise the values of each factor before they can be included in the model for the calculation of the total value at risk. According to the literature [5], the highway risk value normalised to 1 includes vehicle operating speed difference below 20km/h, non-village road sections, non-tunnel road sections, clear lane demarcation line road sections, vibration marking road sections, road-side obstacle-free road sections, hard shoulder width of 0 road sections, intersection road sections and curved road sections with complete safety facilities such as markings and signage, intersection channelisation road sections, and single carriageway road sections, Flat curve radius ≥1500m road section, slope less than 2.5% road section, road section in good condition, anti-skid road section with reasonable sign marking and marking, non-illuminated road section and road section with good sight distance. The model parameters of the relevant road sections are taken according to the actual road conditions and the risk value normalised to take the value of 1 for comparison, and different risk values are taken according to the comparison of high and low risks, and then the risk value of each argumentative element is incorporated into the model for calculation.

2.5. Road risk classification

According to domestic and international experience, when determining the grading threshold standard in risk factor analysis, in addition to providing a fixed-value method, it can also be determined proportionally according to the actual needs, generally dividing the risk score by 20 per cent equally or by the highest 10 per cent (HR > HR90) as level V, and 20 per cent of the higher risk score (HR 90 ≥ HR > HR 70) as level IV, with a total of 30 per cent as the high-risk road section. The selection criteria for high-risk road sections can be relaxed for regions with good economic input conditions, and the final road risk classification results are shown in Table 1.

Table 1 Road Risk Classification Scale

Risk Level	Risk Profile	Range of Road Risk Indicators
V	high risk level	HR≥23
IV	higher risk level	23＞HR≥13
III	medium risk level	13＞HR≥5
II	lower risk level	5＞HR≥3
I	low risk level	HR＜3

2.6. Speed Limit Optimisation

Combined with the design speed, speed limit status quo, operating speed and status quo risk factor analysis results, the proposed overall IV, V high-risk sections of the proportion of 30% (±5) as the objective function for the optimisation of the solution. The objective function is:

$$min\frac{\mathrm{N}_{\mathrm{HR}_{\mathrm{IV}}}+\mathrm{N}_{\mathrm{HR}_{\mathrm{V}}}}{\mathrm{N}_{\mathrm{HR}_{\mathrm{I\sim V}}}} = 30\% \pm (5\%) \tag{2}$$

$$\begin{cases} |V_i - V_{i-1}| \le 20\text{km/h} \\ V_{subway} \le V_{non-tunnel} \\ V_{max} = 120\text{km/h} \\ V_{min} = 60\text{km/h} \end{cases}$$

3. Application examples

3.1. Overview of speed-limited road sections

This paper takes K24+680m ~ K74+780m of Chongqing Hechang Expressway as the object of speed limit, Hechuan-Changshou section of Chongqing Third Ring Expressway is an important section of Chongqing Third Ring Expressway, which belongs to the mountainous and hilly road section, subtropical warm and humid monsoon climate zone, with an average temperature of 18.1°C. The average temperature is 18.1°C, with a high density of bridges and tunnels, and a high ratio of bridges and tunnels. The average temperature is 18.1℃. There are more heavy rain, heavy rain and foggy days, dense bridges and tunnels, heavy ratio, more bridge-cum-tunnel connected sections, and there are many large longitudinal slopes, small radius curves, tunnel exits connecting the intersection exit sections.

3.2. Data collection

After collecting information on national, industry and project location laws and regulations related to speed limits, technical standards or guidelines, highway engineering design and construction documents, traffic volume and geographic information, this paper conducted field surveys including route intersection setup along the routes, access to and from vehicles and people, geometric alignments of interchanging three-dimensional intersections, service areas, parking area ramps, traffic signs and markings other than speed limit signs, guardrail setup; land-use types along the routes, the degree of road-side development; and information on the topography and geomorphology along the routes, geographical features, and the distribution of greening and facilities along the routes.

3.3. Classification of speed limit demonstration units and road technical conditions

In this paper, the direction of the highway left line mileage pile number growth for the positive direction, the direction of the highway right line mileage pile number growth for the reverse direction, this paper argumentation unit division standard to 100m as the standard equal division, from the pile number K24+680 to K74+780 divided into a total of 501 speed limit argumentation unit.

The design speed of Chongqing Hechang Expressway is 80km/h, with four lanes in both directions and a central divider width of 2m. Within the speed-limit section, the forward direction contains 128 speed-limit argumentation units with a level curve radius of less than 1500m, and the reverse direction contains 125 speed-limit argumentation units with a level curve radius of less than 1500m. There are 3 large continuous downhill sections in the speed limit section, K25+227m~K30+515m, K41+750m~K46+40m and K48+670m~K56+425m. The speed limit section is asphalt concrete pavement, and the median divider of the road section adopts split-type waveform beam guardrail. The width of the carriageway is 3.75m, the width of the left kerb strip is 0.5m, and the width of the right hard shoulder is 2.5m. There are four tunnels within the speed limit section, all of which are medium-length tunnels, and the accident pattern of the tunnel is mainly tailgating and scraping of vehicles at the entrance and exit of the tunnel.

3.4. Classification of Speed Limit Roads

3.4.1. Special speed limit identification

According to the special road section identification principle, the special speed limit section identification results of this speed limit section are shown in Table 2.

Tab. 2 List of Special Speed Limit Roads

Argumentation module number	milepost number (of a vehicle)	technical condition
	Positive direction of the road	
13~24	K25+880~K27+080	Small radius sections, special bridges
41~50	K28+680~K29+680	Small radius sections, tunnels
84~99	K32+980~K34+580	small-radius road
143~173	K39+980~K41+980	small radius sections, tunnels
181~184	K42+680~K43+080	interoperable
288~291	K53+380~K53+780	interoperable
313~344	K56+680~K59+080	Interchangeable, small-radius sections
394~419	K64+080~K66+580	Interchangeable, small-radius sections
442~468	K68+780~K71+480	Small radius sections, tunnels
	Reversal of the road	
35~61	K71+480~K68+780	Small radius sections, tunnels
84~108	K66+580~K64+080	Small radius sections, interchanges
159~182	K59+080~K56+680	small-radius road
184~190	K56+580~K55+880	interoperable
211~214	K53+880~K53+480	interoperable
318~320	K43+180~K42+880	interoperable
330~349	K41+980~K39+980	small-radius road
354~359	K39+580~K39+980	interoperable
404~409	K34+580~K33+980	small-radius road
453~463	K29+680~K28+580	Small radius sections, tunnels
479~490	K27+080~K25+880	Small radius sections, special bridges

3.4.2. Determination of speed limit sections

The current speed limit of Chongqing Hechang Expressway is the traditional speed limit by vehicle type, i.e. the speed limit of minibuses is 100km/h, the speed limit of other types of vehicles is 80km/h, and the speed limit of all vehicles in tunnels is 80km/h. According to the general speed limit section division principle in section 1.2, the results of this speed limit section division are shown in Table 3.

Tab. 3 Speed Limit Section Classification Results

Positive direction of the road				Reversal of the road		
General speed limit	Numbering of the argumentation module	milepost number (of a vehicle)	original speed limit	Numbering of the argumentation module	milepost number (of a vehicle)	original speed limit
1	1~43	K24+680~K28+980	100	1~40	ZK74+880~ZK880	80
2	44~82	K28+980~K32+880	80	41~242	ZK70+880~ZK50+680	100
3	83~108	K32+880~K35+480	100	243~277	ZK50+680~ZK47+180	80
4	109~134	K34+980~K38+080	80	278~368	ZK47+180~ZK38+080	100
5	135~225	K38+080~K47+180	100	369~394	ZK38+080~ZK35+480	80
6	226~260	K47+180~K50+680	80	395~420	ZK35+480~ZK32+880	100
7	261~462	K52+680~K70+880	100	421~459	ZK32+880~ZK28+980	80
8	462~501	K70+880~K74+780	80	460~501	ZK28+980~ZK24+780	100

3.4.3. Solving model

Under the original speed limit scheme, the proportion of IV and V risky road sections in the forward and reverse directions of the highway is as high as 54.691% and 54.491% respectively, which exceeds the requirement that the overall proportion of high-risk road sections is close to 30%, and the overall risk level of the highway is high, therefore, under the condition of unchanged infrastructure, the speed limit scheme can be optimised, and the proportion of IV and V risky road sections of the highway can be achieved to be around 30% through regulating the speed limit value.

Through the analysis, we know that only R_1, R_2 and R_4 will have an impact on the risk value of the motorway. Among them, R_113 and R_121 are the most influential factors affecting the value of R_1. At the high-risk road section, the radius of the road section level curve is only 700m~1500m, all of which are in the small-radius road section and located at the entrance and exit of the tunnel, which belongs to the special speed-limiting road section. R_221 is the main influence factor affecting R_2 value, due to the undulating terrain in mountainous areas, there are many ravines and road conditions are poor, so the mountainous highway mostly adopts the integral roadbed, and the width of the central divider of the Hop-Chang Highway is only 2m, so if the vehicle is out of control, the vehicle is very easy to drive through the central divider and collide with the oncoming vehicle head-on. R_413 and R_421 are the main factors affecting the value of R_4. The passive intersection of the motorway also belongs to the accident-prone road section, which is only guided by signs without signals, and the risk factor is high. Therefore, the speed limit value should be appropriately reduced for high-risk road sections to ensure driving safety; on the contrary, for low-risk road sections with good road conditions, the speed limit value can be appropriately increased to enhance the traffic efficiency under the condition of meeting the overall risk requirements.

The overall high risk proportion of the control road is 30% (±5%) for the optimisation solution, and the resulting speed limit optimisation scheme is shown in Table 4. The proportion of high-risk road sections with road risk value greater than 13 is 30.900% and 32.140% in positive and negative directions respectively, which is reduced by 23.791% and 22.351% compared with the original scheme, so that the overall risk of the road is effectively controlled.

Tab. 4 Speed limit optimisation results

speed limit zone	Positive direction of the road	Reversal of the road
	speed limit value（km/h）	
1	100	90
2	80	90
3	100	90
4	80	90
5	90	90
6	90	90
7	90	90
8	90	90

3.4.4. Optimisation results of the speed limit programme

As can be seen from Fig. 1, under the new speed limit scheme, the overall risk of the forward direction of the Hechang Expressway is controlled at level III, and the high-risk road sections are mainly concentrated in the 1, 3, 6 and 8 road sections, and the biggest influencing factor affecting the risk of highway at speed limit sections 1 and 3 is R_2, of which R_221 is also the biggest influencing factor affecting the value of R_2. The width of median band is recommended to strengthen the guardrail grade if it can't be changed, to prevent the speeding and overloading vehicles crossing the median and having head-on collisions with oncoming vehicles. Speed limit sections 6 and 8 are tunnel sections. As there is no hard shoulder inside the tunnel, the consequences of a vehicle accident would be very tragic. It is recommended that reasonable measures be taken at the tunnel portal to reduce the black hole effect; and that reasonable measures be taken to reduce the number of traffic accidents caused by kerbstones and emergency stopping zones inside the tunnel. The remaining high-risk sections of the forward speed limit road are all at the diversion and merging points of interchanges and service areas, and reasonable graded speed limits should be adopted for transition.

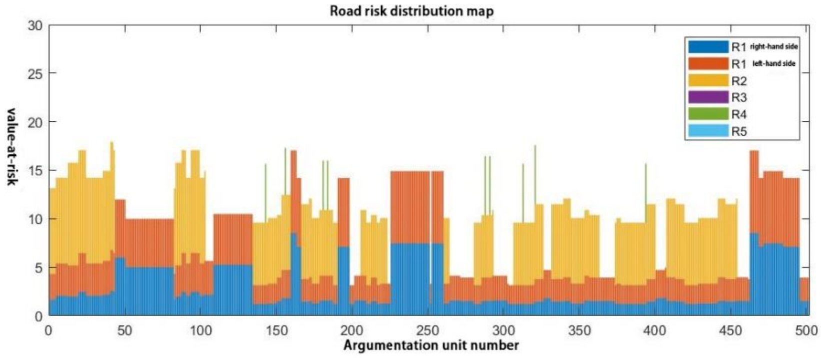

Fig. 2 Risk distribution map after optimisation of the road forward speed limit scheme

From Figure 5, it can be seen that under the new speed limit scheme, the overall risk control of the reverse direction of the Hechang Expressway is at level III, and the high-risk road sections are mainly concentrated in the speed limit sections 1, 3, 5, and 7, and all the high-risk road sections are all tunnels, and their accident prevention suggestions are consistent with section 2.4.4. The remaining high-risk road sections within the reverse speed limit section are all at the diversion and merging of interchanges and service areas, and reasonable graded speed limits should be adopted for the transition of this section.

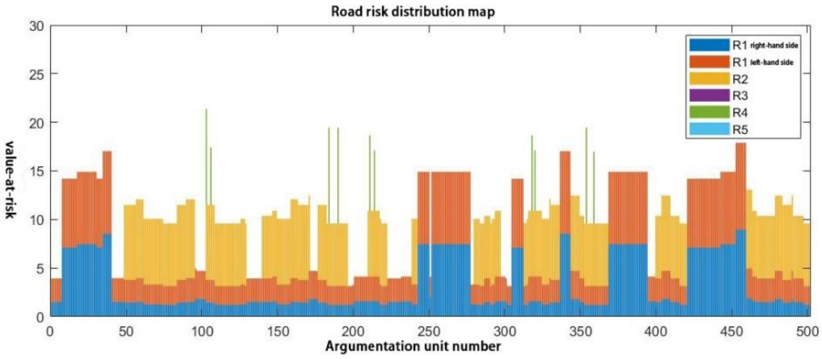

Fig. 5 Risk distribution map after optimisation of the road reverse speed limit scheme

4. Conclusion

Traffic safety is a hot issue of social concern, always related to the safety and efficiency of road transport. Most of the traditional speed limits in China only focus on transport efficiency, while ignoring the element of driving safety, so speed limit value researchers need to build a safe traffic environment for highway users from the perspective of active safety, while taking into account the efficiency of access.

1) Compared with the traditional highway speed limit mode, this paper comprehensively analyses the accident types and road alignment conditions, and uses the risk factor analysis method to incorporate the highway accident risk into the formulation of speed limit scheme, and obtains a better control effect.

2) The use of the risk factor analysis model enables the overall road risk to be effectively controlled, and the results show that the forward road risk of the Hechang Expressway has been reduced by 23.791 per cent, while the reverse road risk has been reduced by 22.351 per cent.

3) Different optimisation logics may yield different results when using the program for optimal solution solving, and the optimal speed limit solution for this road section will be optimised as the program is optimised.

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