Hindawi Publishing Corporation
Mathematical Problems in Engineering
Volume 2014, Article ID 403560, 8 pages
http://dx.doi.org/10.1155/2014/403560

Research Article

Study on Evaluation Models of Highway Safety Based on Catastrophe Theory

Hezheng Bi,[1] Linjun Lu,[1] Jian Lu,[1] and Chen Wang[2]

[1] *School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, 800 Dongchuan Road, Minhang District, Shanghai 200240, China*
[2] *School of Transportation Engineering, Tongji University, 4800 Cao'an Road, Jiading District, Shanghai 201804, China*

Correspondence should be addressed to Linjun Lu; linjun.lu@yahoo.com

Received 22 July 2014; Accepted 12 September 2014; Published 29 September 2014

Academic Editor: Wuhong Wang

Evaluating safety performance of first-class highways in China is important due to their high mortality rates. Traditional models for statistical crash prediction and traffic conflict techniques require long periods of data collection which is time-consuming and labor-intensive. This paper introduces a safety evaluation method based on catastrophe theory for highways in China. The method firstly divides the highway into multiple road sections and uses video-based road detection (VRD) system to collect video data of existing road conditions. Then, experienced drivers and experts are invited to watch the collected videos to establish a multilayer safety index system and assign values to bottom indexes. By applying catastrophe theory, a general safety index is derived, which indicates the relative safety level of a road section. Finally, all road sections can be ranked based on the general safety index. A case study shows encouraging results where (1) the safety index is highly correlated with real mortality rates and (2) the safety index successfully identifies most dangerous road sections. The proposed method can be considered as a promising supplementary safety evaluation method that could help traffic engineers to better understand safety implications of first-class highways in China.

1. Introduction

The mortality rates (deaths per 100 km per year) of highways are unevenly distributed in China. First-class highways that only account for 1.79% of the total highway mileage have the highest mortality rate (36.16 deaths per 100 km per year), followed by second-class highways (16.18 deaths per 100 km per year) and expressways (15.53 deaths per 100 km per year). Thus, first-class highways can be considered as the most dangerous roadway type in China, which certainly deserves careful safety evaluations.

Safety evaluations can help to develop effective safety countermeasures to lower crash rates and reduce crash severity. Figure 1 shows the scope of safety evaluations that can be applied in different time stages including design, construction, and operation and can be evaluated at different levels (i.e., macro-, meso-, and microlevels) [1]. Different evaluation methods are utilized depending on specific purposes. This paper will be focused on the mesolevel safety evaluations on first-class highways in China at the operation stage.

Table 1 demonstrates the scope and objective of safety evaluations on first-class highways in China at three levels. Macrolevel safety evaluations focus on an entire highway to improve overall road safety. Microlevel safety evaluations examine detailed information including road characteristics, human behaviors, and traffic flows, in order to evaluate safety of a specific location or traffic facility (e.g., an intersection). A first-class highway generally goes through multiple provinces and administrative regions, which could have significantly different land-use, demographic, and social-economic characteristics. Therefore, examining the overall safety of a first-class highway (i.e., macrolevel safety evaluations) is not enough to understand the safety issues of different areas and road sections. On the other hand, a first-class highway generally has long length and enormous traffic facilities, which makes it time-consuming and labor-intensive to evaluate every single traffic facility (microlevel

Table 1: Safety evaluations on first-class highways in China at different levels.

Evaluation level	Evaluation scope	Primary objective
Macrolevel	The entire highway	Understand the overall safety of the entire highway
Mesolevel	Road sections	Understand the safety of road sections and identify dangerous road sections for further in-depth analysis
Microlevel	Certain facility and road spot	Find out safety issues of the specific locations/traffic facilities and provide countermeasures

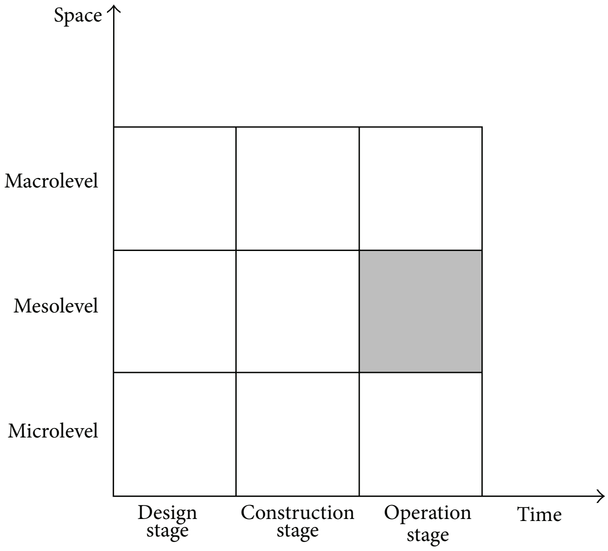


Figure 1: The scope of safety evaluations.

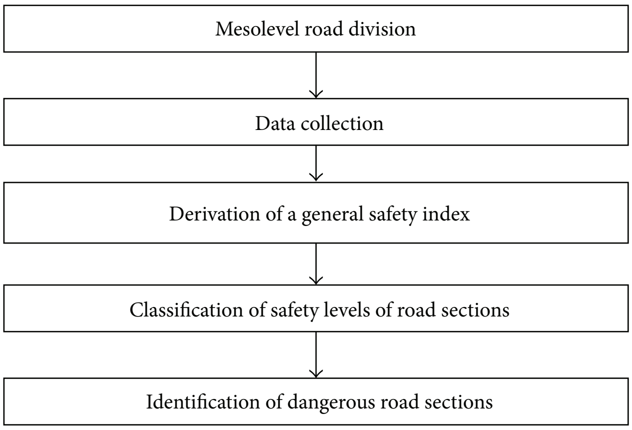


Figure 2: The flow process of the mesolevel safety evaluation method for first-class highways in China.

evaluations). Consequently, evaluating road sections (i.e., mesolevel evaluations) could be considered as a more cost-effective way to provide enough useful information that can allow traffic professionals to further conclude overall road safety or identify dangerous road sections that require further in-depth safety analysis.

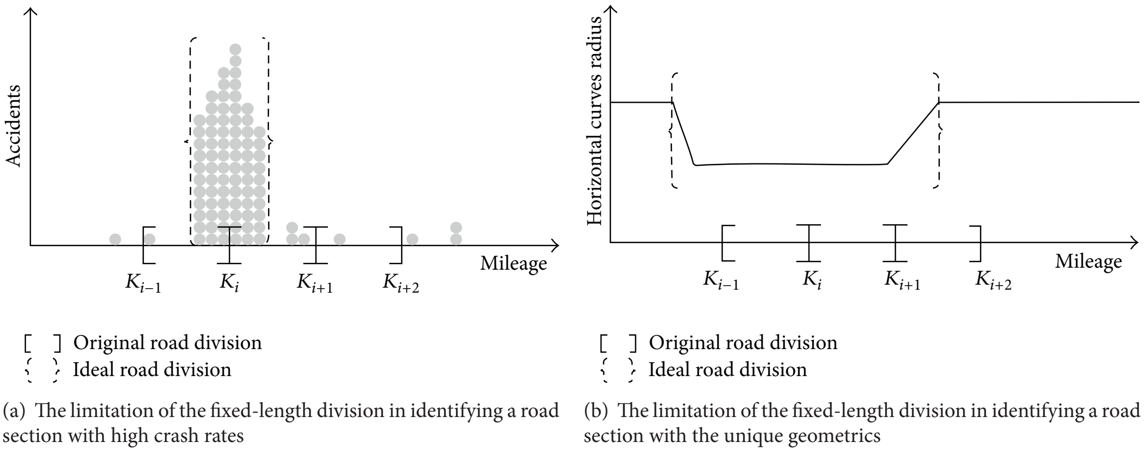
Traditional safety evaluations are mostly based on historical crash data or traffic conflict data. However, it is difficult to obtain sufficient reliable crash data for a highway which basically has long length and runs across multiple regions. A study performed by Turner and Mansfield in 1983 indicates that about 25% of urban traffic crash records and 20% of rural traffic crash records in Alabama State in USA were mistakenly recorded [2]. Traffic conflict techniques have been attempted to analyze traffic safety performance of roadway intersections in recent years [3–7]. But one limitation of such techniques is that the identification of traffic conflicts and their type relies on the experiences and knowledge of observers, which could easily generate human bias and adversely affect data reliability. Besides, collecting conflict data of an entire highway is a very challenging task even using automated video techniques. In recent years, some comprehensive evaluation methods have been developed by researchers. In 2008, Lu et al. introduced the concept of level of safety service and developed a noncrash based model for safety evaluation [8]. Yuan and Lu also presented a diagnostic approach for safety evaluation which is based on road characteristics [9]. Most of these methods can only be applied to intersections which limit their usage in highway safety evaluations.

Notably, some risk-based approaches were also utilized to evaluate road safety. The Highway Safety Manual provides quantitative information for decision making based on safety performance of road and facilities. It assembles currently available information and methodologies on measuring, estimating, and evaluating roadways in terms of crash frequency (number of crashes per year) and crash severity (level of injuries due to crashes) [10]. The U.S. Road Assessment Program has developed a protocol to assign ratings to roads on the basis of the presence or absence of key design features related to safety. This protocol rates roads by assigning them one to five stars according to approximately 20 key roadway safety features [11]. However, these methods, such as safety performance functions (SPFs) of HSM or the iRAP methodology, still require crash modification factors (CMF) that were derived based on historical data. As stated earlier, reliable crash data in China are severely lacking, which prevents these methods from being applied in practice.

To fill this gap, a new comprehensive method will be introduced to evaluate the safety of first-class highways in China at the mesolevel. Also, the method requires neither historical crash data nor time-consuming field observations.

2. Methodology

Figure 2 shows the whole process of the proposed safety evaluation method. Firstly, a first-class highway is divided



(a) The limitation of the fixed-length division in identifying a road section with high crash rates

(b) The limitation of the fixed-length division in identifying a road section with the unique geometrics

FIGURE 3: The limitation of the fixed-length division method.

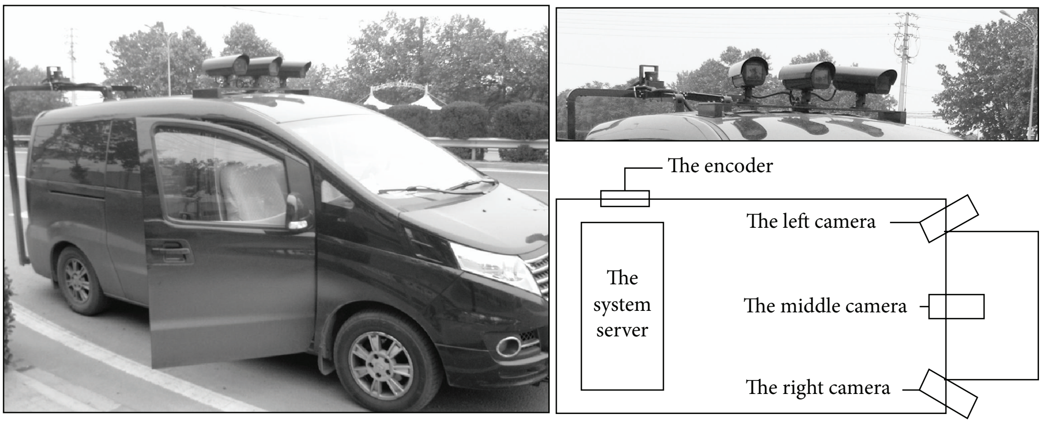


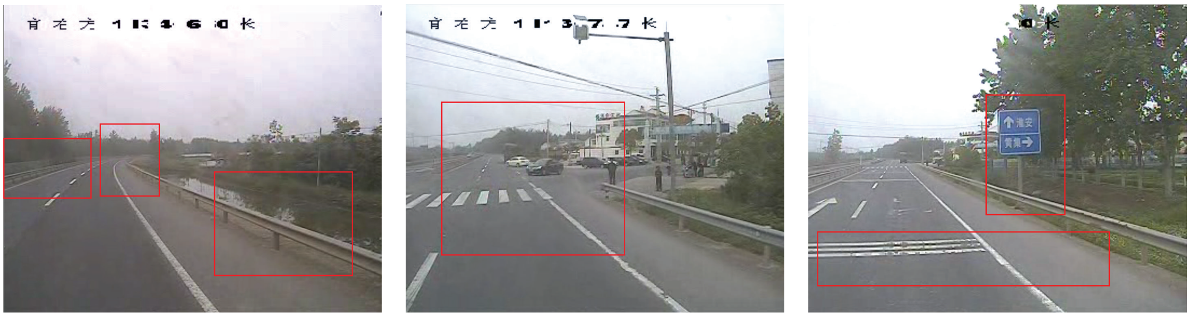
FIGURE 4: The video-based road detection (VRD) System.

into multiple road sections (i.e., mesolevel). Then, the road information (e.g., geometrics, pavements, etc.) of each highway section is recorded in video data. After that, experienced drivers and experts are invited to watch the collected videos and determine the safety impacts of various variables on each road section. Next, a catastrophe model is applied to generate a safety index, which indicates the relative safety level of each road section. Finally, all road sections are ranked by their safety levels based on the safety index and dangerous road sections are identified. The following subsections will address each step of the process in detail.

2.1. Mesolevel Road Division. The first step of the method is to divide a highway into multiple sections based on certain criteria. The fixed-length division method and the nonfixed division method are the two commonly used methods for road divisions [12]. The fixed-length division method is easy to conduct but has obvious limitations: roads are subjectively divided into the same length without considering factors such as traffic volumes, road geometrics, and traffic crashes. Thus, when used in practice for special purposes (e.g., safety evaluations), this method is not capable of identifying the crucial road sections or road sections with similar features. In Figure 3(a), the nonfixed division method fails to identify a road section with extremely high crashes. In Figure 3(b), the nonfixed division method fails to identify a unique road section that has different curve radius from all other sections.

The nonfixed division method has been considered to have advantages over the fixed-length division method [13–15]. It is based on the internal links among road characteristics such as traffic volume, speed limit, lane allocations, horizontal/longitudinal curves, and cross-section types. A highway can be divided into different lengths according to road characteristics for certain purposes. Expert panels and cluster analysis method are commonly used to conduct nonfixed road divisions.

2.2. Data Collection. All required video data are collected by a video-based road detection (VRD) system that consists of a video capture terminal, a system server, and a client terminal, as is shown in Figure 4. The video capture terminal consists of 3 high-speed cameras which record road/traffic conditions from different angles. A sensor installed in a vehicle will transmit videos and data (including time, road stake number, and vehicle speed) to the system server. The system server is equipped with the vehicular industrial computer system,



(a) Median and horizontal curves and shoulders and barriers

(b) Traffic controls and pavement markings

(c) Traffic signs and road surface

Figure 5: The examples of video data collections.

which is used to save and process the data. The client terminal shows the real-time road videos.

The VRD system captures road and traffic videos from the perspective of road users (i.e., drivers). Video data can be watched repeatedly to ensure that all important details are examined. Thus, compared to traditional field-based observations, the VRD system significantly improves efficiency and accuracy of road data collections. Figure 5 shows some examples of video images extracted from the VRD system.

2.3. Derivation of a General Safety Index Based on Catastrophe Theory. Catastrophe theory, proposed by the French mathematician René Thom in the book "Structural Stability and Morphogenesis," addresses the process of how a series of small internal changes could result in a significant and sudden external change [16]. Thom regards the overall "jump" process as a catastrophe. This theory can be used to analyze and predict complex dynamical systems.

A traffic catastrophe means that the internal changes in a traffic system cause the unbalance of the system and thus result in external changes. A traffic system can be described by a group of variables including road alignment, pavement, signs, markings, control, and signals. If any small changes happen to one of those variables, the system balance could be broken and external changes (e.g., traffic crashes) could happen.

Catastrophe theory only requires the ranks of variables according to their importance to the system. Therefore, assigning weights to variables is unnecessary, which are mostly required by other fuzzy methods such as the analytic hierarchy process (AHP) and the fuzzy interval method (FIM) [17]. The derivation of a general safety index based on catastrophe theory can be conducted by the following 3 steps.

2.3.1. Step 1: Establish a Multilayer Index System. In order to apply catastrophe safety evaluation models, a multilayer index system needs to be established firstly. The top-layer index should be a general safety index that indicates the overall safety level of the specific road section under safety evaluation. We first come up with the initial indexes based on literature and field research. And 15 experts are invited to give each index a score within the range 1 to 5 according to its practical influence on the overall safety. According to clustering analysis and expert panels, traffic conditions of intersections, geometric designs, road facilities, and road environment are selected as the four second-layer indexes that significantly influence the safety of first-class highways in China. The four second-layer indexes are further subdivided into 13 third-layer indexes according to experts. Table 2 shows the multilayer index system of first-class highways. In order to apply catastrophe theory, subindexes in the same group are ranked in a top-down manner, according to their importance to the main index. For example, the bottom-layer indexes A41, A42, A43, and A44 need to be ranked according to their importance to the second-layer index A4. The ranks can be determined by various methods such as statistical analysis and expert based scoring. Notably, for different road sections, the ranks of indexes can be determined to be different, depending on the characteristics of road sections.

The following briefly address the four indexes at the second layer.

(1) Intersections. Highway intersections have much more crashes compared to other road sections, due to complex traffic control strategies and numerous vehicle interactions (i.e., conflicts). According to historical crash data, in the USA, about 55% of total traffic crashes and 23% of fatal traffic crashes in urban areas happened at intersections and about 32% of total traffic crashes and 16% of fatal traffic crashes in rural areas happened at intersections [18]. In China, about 30% of urban traffic crashes happened at intersections and about 47% of rural traffic crashes happened at intersections [19]. These indicate that the intersection characteristics need to be carefully examined.

(2) Road Environment. Attractive road environment could make drivers feel comfortable and influence drivers' actual behaviors in a positive way including driving aggressiveness, speed choice, and conformity to traffic rules [20].

(3) Geometric Designs. Previous studies have shown that inappropriate geometric highway designs are highly associated with increased crash risks. For example, an inappropriate design of road alignment and sight distance could confuse drivers and increase their workloads and driving risks [21].

Table 2: The multilayer index system of first-class highways.

The general safety index	Second-layer index	Bottom-layer index
The safety level of a road section	Intersections A_1	Traffic flows A_{11}
		Traffic controls A_{12}
		Channelization A_{13}
	Road environment A_2	Road surface condition A_{21}
		Minor access point density A_{22}
		Roadside design/obstacle A_{23}
	Geometric designs A_3	Quality of curve A_{31}
		Sight distance A_{32}
		Lane width and shoulder width A_{33}
	Road facilities A_4	Medians A_{41}
		Barriers A_{42}
		Street lightings A_{43}
		Delineation A_{44}

A wide median can effectively reduce the likelihood of head-on crashes [22]. Therefore, geometric elements need to be examined to ensure that they are properly designed.

(4) Road Facilities. Road facilities such as barriers, lightings, and signs play very important roles in highway safety. Functional road facilities will effectively provide drivers with guidance and protection. Thus, functional road facilities can ensure the safety performance of a highway.

2.3.2. Step 2: Assign Original Values to Bottom-Layer Indexes. Three steps need to be conducted: (1) experienced drivers and road safety professionals are invited to watch the video data of each road section collected by the VRD system; (2) experts evaluate each road section and assign an initial value $\{a_{ij}\}$ to each bottom index based on their knowledge and experiences; (3) standardize $\{a_{ij}\}$ to get the standardized value $\{A_{ij}\}$ of each index.

A higher value $\{a_{ij}\}$ indicates a safer condition. For example, if an expert gives 0 to the index of road surface condition for a certain road section (score ranges from 0 to 10), he/she considers the surface condition of this road section to be extremely unsafe to road users.

The standardized value can be calculated by

$$A_{ij} = \frac{a_{ij} - a_{\min}}{a_{\max} - a_{\min}}, \tag{1}$$

where A_{ij} is the standardized value of the jth important bottom index that is a subdivision of the ith second-layer index; $a_{\max}$ are the maximum values that can be assigned to a bottom index; $a_{\min}$ are the minimum values that can be assigned to a bottom index.

2.3.3. Step 3: Calculate the Value of the Top-Layer Index. With known values of bottom-layer indexes, the intermediate catastrophe values can be calculated according to

$$X_{ij} = A_{ij}^{1/(j+1)}, \tag{2}$$

where X_{ij} is the intermediate catastrophe value of jth important bottom index that is a subdivision of the ith second-layer index.

After the intermediate catastrophe values are determined, "complementary" and "noncomplementary" rules should be considered when deciding the original higher-level values. The "complementary" rule means that the impact of an index on its higher-level index can be replaced by other indexes. For those indexes, the original values of second-layer indexes can be derived by

$$A_i = \frac{X_{i1} + \cdots X_{ij} \cdots + X_{ik}}{k}, \tag{3}$$

where A_i is the original value of the ith second-layer index and k is the total number of bottom indexes that belong to the ith second-layer index.

"Noncomplementary" indexes are the indexes with significant impact on the higher-level index, which cannot be ignored. For those bottom indexes, the original values of the second-layer indexes can be calculated by

$$A_i = \min\left\{X_{i1}, \ldots, X_{ij}, \ldots, X_{ik}\right\}. \tag{4}$$

When the second-layer indexes are known for their original values, formula (2) can be utilized again to derive the intermediate catastrophe values of the second layer. Thus, the catastrophe value of the top-layer index (i.e., the general safety index) can be derived through this recursive algorithm. For first-class highways, the value of the top-layer index (i.e., the general safety index) can be derived using the "noncomplementary" rule since the four second-layer indexes are all very important factors that cannot be ignored.

2.4. Safety Levels Classification. Calculate the values of the top-layer index when all bottom-layer values are assigned. Table 3 shows the top-layer values, assuming that all bottom-layer indexes have the same values from 0 to 1 with the increment of 0.1.

Table 3: Bottom-layer values and catastrophe values of the general safety index.

Bottom-layer values	0	0.1	0.2	0.3	0.4	0.5
Top-layer value	0	0.669	0.753	0.808	0.849	0.884
Bottom-layer values	0.6	0.7	0.8	0.9	1	
Top-layer value	0.913	0.938	0.961	0.981	1	

Table 4: Classification and description of mesolevel safety levels of first-class highways.

Level	Value	Qualitative description
Excellent	(0.981, 1)	A highway section with excellent safety performance which does not require safety improvement.
Good	(0.938, 0.981)	A highway section with good safety performance which has some safety issues that need to be examined and improved.
Fair	(0.884, 0.938)	A highway section with fair safety performance which has a considerable number of safety issues that need to be carefully examined.
Poor	(0, 0.884)	A highway section with poor safety performance that needs to be thoroughly examined.

Based on experts, the safety of a first-class highway section is determined to be four levels from poor to excellent (shown in Table 4).

Identification of Dangerous Road Sections. According to the safety level classifications, each road section's relative safety level can be determined. The road sections with low safety levels need to be carefully examined through in-depth safety evaluations to identify safety issues and develop countermeasures.

3. Experimental Validations

In our experimental validations, the mesolevel safety evaluation method was applied to evaluate the safety performance of National Highway G205 in Jiangsu province (Figure 6). G205 is 318 km in total length, including 263 km of a first-class highway section across Xuzhou, Suqian, Huaian, and Nanjing city in Jiangsu. It is an important part of the north-to-south transportation corridor in China, connecting multiple expressways and highways. As an open highway, G205 has complex traffic environment, heavy mixed traffic, and frequent access points.

3.1. Mesolevel Road Division. G205 in Jiangsu province runs across multiple cities which have various road characteristics, traffic conditions, and land environments. After expert panel discussions, the first-class highway was finally divided into 10 different road sections by the demarcation of administrative zones.

3.2. Data Collections. The VRD system was utilized to record data of G205 Jiangsu section. Then, 10 experienced drivers and 10 traffic professionals were invited to evaluate safety of each road section according to video data and assign initial values (from 0 to 1) of bottom-layer indexes for each road section.

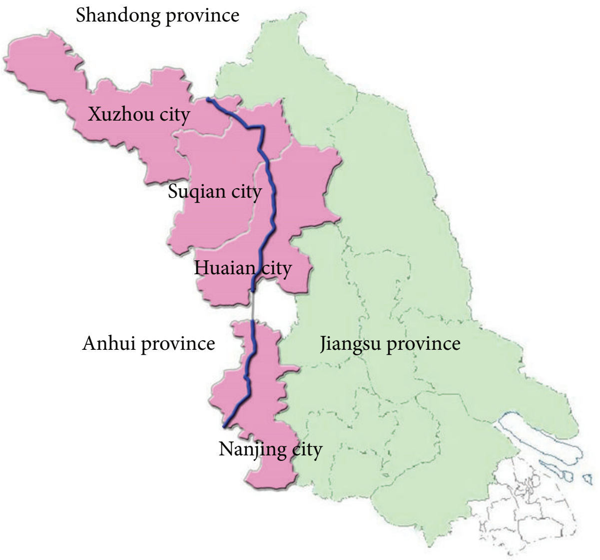


Figure 6: National Highway G205 in Jiangsu province.

3.3. Derivation of the General Safety Index. Taking Section 4 as an example, by applying catastrophe safety evaluation models, the catastrophe values at all layers and the general safety index can be derived. Table 5 shows the catastrophe values of Section 4.

3.4. Determination of Safety Ranks and Identification of Dangerous Road Sections. Likewise, the general safety indexes of the other 9 road sections can also be derived. All road sections' safety is ranked based on their general safety indexes. Table 6 shows the safety rank of 10 sections based on the general safety index as well as the safety rank based on mortality rates (deaths per 100 km per year).

Table 5: Catastrophe values at all layers and the general safety index (Section 4).

Third-layer index		Intermediate index		Second-layer index		Intermediate index		General safety index
A_{11}	0.70	x_{11}	0.837	A_1	0.896	x_1	0.947	0.944
A_{12}	0.73	x_{12}	0.900					
A_{13}	0.82	x_{13}	0.952					
A_{21}	0.72	x_{21}	0.849	A_2	0.842	x_2	0.944	
A_{22}	0.45	x_{22}	0.766					
A_{23}	0.69	x_{23}	0.911					
A_{31}	0.79	x_{31}	0.889	A_3	0.819	x_3	0.951	
A_{32}	0.55	x_{32}	0.819					
A_{33}	0.50	x_{33}	0.841					
A_{41}	0.70	x_{41}	0.837	A_4	0.837	x_4	0.965	
A_{42}	0.72	x_{42}	0.896					
A_{43}	0.56	x_{43}	0.865					
A_{44}	0.70	x_{44}	0.931					

Table 6: Safety ranks based on mesolevel safety evaluations and historical crash data.

Section	Mesolevel safety evaluations			Historical crash data	
	General safety index	Safety level	Rank	Mortality rate (death per 100 km per year)	Rank
Number 1	0.956	Good	3	23	5
Number 2	0.963	Good	2	14	2
Number 3	0.981	Excellent	1	10.5	1
Number 4	0.944	Good	4	17.86	3
Number 5	0.938	Fair	8	90	10
Number 6	0.939	Good	7	19.22	4
Number 7	0.943	Good	5	38.43	9
Number 8	0.941	Good	6	29.17	7
Number 9	0.881	Poor	10	31.25	8
Number 10	0.933	Fair	9	25	6

Spearman rank tests were carried out between the general safety index and mortality rates. The Spearman coefficient is 0.709, which indicates significant rank correlation between the two variables. Moreover, the general safety index successfully identifies 4 of the top 5 crash-prone road sections.

4. Discussion and Conclusions

This paper proposes a mesolevel safety evaluation method based on the video-based road detection (VRD) system for first-class highways in China. The method firstly divides a first-class highway into multiple road sections and uses the VRD system to collect video data of existing road conditions. Then, experienced drivers and experts are invited to watch the collected videos to establish a multilayer safety index system and assign values to bottom indexes. By applying catastrophe theory, a general safety index (i.e., the top index) is derived, which indicates the relative safety level of a road section. Finally, all road sections' safety can be ranked and dangerous road sections are thus identified, based on the general safety index. The experimental validations show that (1) the safety index is highly correlated with real mortality rates and (2) the safety index successfully identifies most dangerous road sections.

Although the validations have shown encouraging results, there are still some issues that need to be addressed here. Firstly, this method can only estimate the relative safety of each road section. The general safety index cannot be directly used as a predictor of mortality rates or crash rates. Thus, the method can only be used as a supplementary safety evaluation method when crash/conflict data are lacking or missing. The second issue is that there is no widely accepted criterion for mesolevel road divisions. Expert panels need to be established to determine the criteria of road division. However, even experienced experts could have very different opinions on selecting certain criteria to divide highways. Thus, the mesolevel road division needs to be carefully conducted. Besides, this evaluation method is only developed for first-class highways in China. Thus, the usage of this method is limited. Future studies can be conducted to improve the method to allow for safety evaluations on other highway types in China.

Another issue that needs to be addressed is that the method is based on catastrophe theory that requires human decisions on ranks/values of indexes. Although twenty experienced experts were invited to reduce human bias and catastrophe theory does not require index weights compared to other fuzzy methods, the method still needs to be further validated and the index system needs to be improved to include more contributing factors.

Although the proposed method requires human judgment, the introduction of advanced data collection technology (i.e., the VRD system) allows experts to thoroughly examine road/traffic details according to video data which could reduce human errors. Catastrophe theory avoids the process of subjectively determining index weights compared to other fuzzy methods, which further reduces human bias. In general, this approach has shown its strength and potential to be used as a supplementary safety evaluation method that could help traffic engineers to better understand safety implications of first-class highways in China and to identify dangerous road sections that require further in-depth safety analysis, when reliable crash/conflict data are missing or lacking.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

References

[1] J. Barceló, J. Casas, D. García, and J. Perarnau, "Methodological notes on combining macro, meso and micro models for transportation analysis," in *Workshop on Modeling and Simulation*, Sedona, Ariz, USA, 2005.

[2] D. S. Turner and E. R. Mansfield, "Variability in rural accident reporting," *Transportation Research Record: Journal of the Transportation Research Board*, no. 910, pp. 8–13, 1983.

[3] E. Hauer and P. Garder, "Research into the validity of the traffic conflicts technique," *Accident Analysis and Prevention*, vol. 18, no. 6, pp. 471–481, 1986.

[4] T. Sayed and S. Zein, "Traffic conflict standards for intersections," *Transportation Planning and Technology*, vol. 22, no. 4, pp. 309–323, 1999.

[5] H.-C. Chin and S.-T. Quek, "Measurement of traffic conflicts," *Safety Science*, vol. 26, no. 3, pp. 169–185, 1997.

[6] C. Kindler, "The intersection diagnostic review module: an expert system for geometric design review of intersections on rural two-lane highways," in *Proceedings of the 82nd Annual Meeting of the Transportation Research Board*, Washington, DC, USA, 2003.

[7] H. E. Ross Jr., D. L. Sicking, and R. A. Zimmer, "Recommended procedures for the safety performance evaluation of highway features," NCHRP Report 350. TRB, National Research Council, Washington, DC, USA, 1993.

[8] J. Lu, F. Pan, and Q. Xiang, "Level-of-safety service for safety performance evaluation of highway intersections," *Transportation Research Record*, no. 2075, pp. 24–33, 2008.

[9] L. Yuan and J. Lu, "Safety evaluation and improvements for highway intersections," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2060, pp. 46–52, 2008.

[10] American Association of State Highway and Transportation Officials, *Safety Manual*, American Association of State Highway and Transportation Officials, Washington, DC, USA, 2010.

[11] D. W. Harwood, "Validation of US road assessment program star rating protocol application to safety management of US roads," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2147, pp. 33–41, 2010.

[12] E. Hauer, J. Kononov, B. Allery, and M. S. Griffith, "Screening the road network for sites with promise," *Transportation Research Record*, vol. 1784, pp. 40–51, 2002.

[13] A. Vogt and J. G. Bared, "Accident models for two-lane rural roads: segments and intersections," Tech. Rep. FHWA-RD-98-133, Federal Highway Administration, Washington, DC, USA, 1998.

[14] Transportation Research Board, *NCHRP Web Document 62 (project 17-18(4)): Contractor's Final Report: Development of a Highway Safety Manual*, Transportation Research Board, Washington, D.C., USA, 2003.

[15] S. P. Miaou, P. S. Hu, and T. Wright, "Development of relationships between truck accidents and highway geometric design: phase I," Tech. Rep. FHWA-RD-91-124, Federal Highway Administration, Washington, DC, USA, 1993.

[16] P. T. Saunders, *An Introduction to Catastrophe Theory*, Cambridge University Press, New York, NY, USA, 1980.

[17] S. Feng and L. D. Xu, "Decision support for fuzzy comprehensive evaluation of urban development," *Fuzzy Sets and Systems*, vol. 105, no. 1, pp. 1–12, 1999.

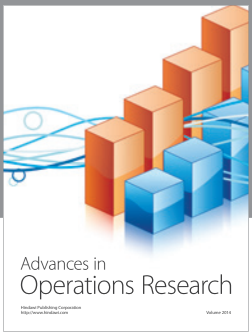
[18] Iowa Safety Management System, *Toolbox of Highway Safety Strategies*, Iowa Department of Transportation, Ames, Iowa, USA, 2002.

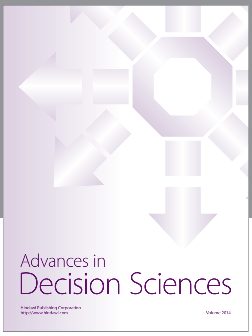
[19] X. Liu and H. Duan, "Methods of traffic safety evaluation at grade intersection," *Chinese Journal of Ergonomics*, vol. 3, no. 2, pp. 49–53, 1997.

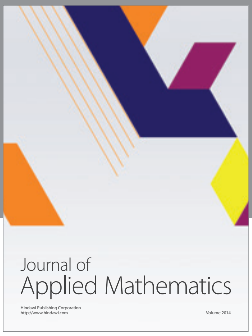
[20] X. Wu and X. Wang, "Evaluating alignment consistency for mountainous expressway in design stage: a driving simulator-based approach," in *Proceedings of the 92nd Annual Meeting of the Transportation Research Board*, Washington, DC, USA, 2013.

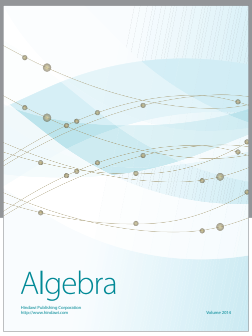
[21] K. Dixon, M. Liebler, and M. Hunter, "Urban roadside safety: cluster-crash evaluation," *Transportation Research Record*, vol. 2120, pp. 74–81, 2009.

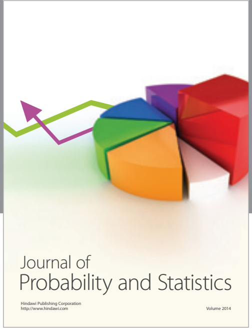
[22] D. L. Sicking, F. D. B. de Albuquerque, K. A. Lechtenberg, and C. S. Stolle, "Guidelines for implementation of cable median barrier," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2120, pp. 82–90, 2009.


Advances in
Operations Research

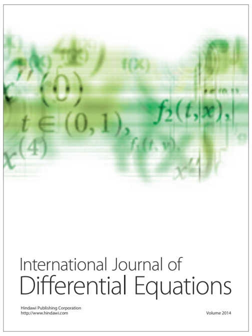

Advances in
Decision Sciences


Journal of
Applied Mathematics

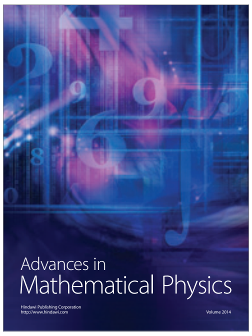

Algebra

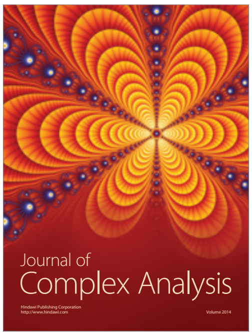

Journal of
Probability and Statistics

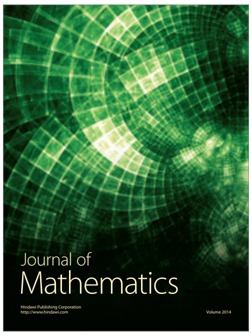

The Scientific
World Journal

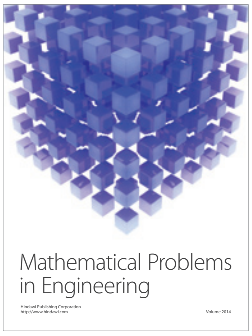

International Journal of
Differential Equations

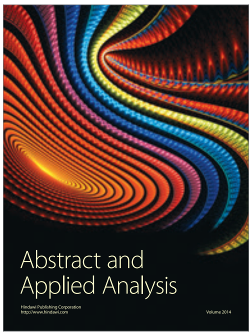

International Journal of
Combinatorics

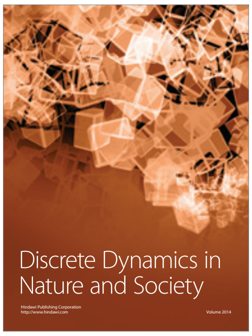

Advances in
Mathematical Physics

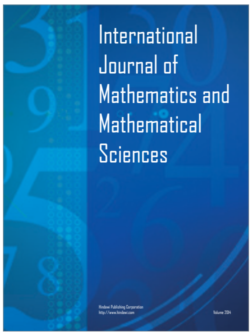

Journal of
Complex Analysis


Journal of
Mathematics


Mathematical Problems
in Engineering

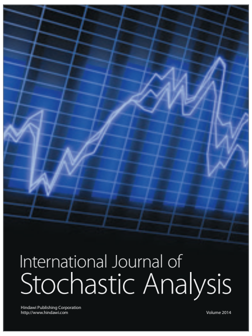

Abstract and
Applied Analysis


Discrete Dynamics in
Nature and Society


International
Journal of
Mathematics and
Mathematical
Sciences


Journal of
Discrete Mathematics


Journal of
Function Spaces


International Journal of
Stochastic Analysis


Journal of
Optimization