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Research Article

Engineering Solutions to Enhance Traffic Safety Performance on Two-Lane Highways

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Improving two-lane highway traffic safety conditions is of practical importance to the traffic system, which has attracted significant research attention within the last decade. Many cost-effective and proactive solutions such as low-cost treatments and roadway safety monitoring programs have been developed to enhance traffic safety performance under prevailing conditions. This study presents research perspectives achieved from the Highway Safety Enhancement Project (HSEP) that assessed safety performance on two-lane highways in Beijing, China. Potential causal factors are identified based on proposed evaluation criteria, and primary countermeasures are developed against inferior driving conditions such as sharp curves, heavy gradients, continuous downgrades, poor sight distance, and poor clear zones. Six cost-effective engineering solutions were specifically implemented to improve two-lane highway safety conditions, including (1) traffic sign replacement, (2) repainting pavement markings, (3) roadside barrier installation, (4) intersection channelization, (5) drainage optimization, and (6) sight distance improvement. The effectiveness of these solutions was examined and evaluated based on Empirical Bayes (EB) models. The results indicate that the proposed engineering solutions effectively improved traffic safety performance by significantly reducing crash occurrence risks and crash severities.

1. Introduction

Improving two-lane highway traffic safety conditions is of practical importance and has attracted significant research attention within the last decade. Many cost-effective and proactive solutions such as low-cost treatments and roadway safety monitoring programs have been developed to enhance traffic safety performance under prevailing conditions. A two-lane Highway Safety Enhancement Project (HSEP) was implemented on the major highway network in Beijing from 2004 to 2006 by the Ministry of Transport of the People's Republic of China. A series of engineering solutions was proposed and integrated to improve traffic safety performance network-wide. More than 170,000 hazardous sections of national or provincial highways were improved over 50,000 kilometers, which included improper curves, heavy gradients, insufficient sight distances, and vague clear zones. Cost-effective countermeasures against severe injuries and fatal crashes also included adding or replacing traffic signs, painting markings on pavement, installing different barriers on roadsides, and channelizing intersections.

Substantial work has been conducted on engineering-based countermeasure development for improvement of safety performance. Bagdade et al. [1] introduced specific traffic engineering improvements targeted at improving safety for seniors, which were developed to popularize the use of a number of engineering countermeasures throughout Michigan. Labi [2] investigated the efficacy of roadway improvements in terms of crash reduction at various subclasses of rural two-lane highways using the empirical analysis method of the negative binomial modeling technique. However, most of these previous studies focused on only a single improvement, that is, widening shoulders, adding passing lanes, or installing center left-turn lanes. Schneider et al. [3] and Bauer and Harwood [4] presented safety prediction models and conducted evaluations of safety effects of horizontal curves on rural two-lane highways. Their findings showed that the radius and length of each horizontal curve significantly influenced the frequency of crashes. Gross et al. [5, 6] and Schrock et al. [7] explored the use of observational data to estimate safety effectiveness for changes in lane and shoulder width and found that adding passing lanes was an economical and effective safety improvement for rural two-lane highways. These findings can be used to help determine cost-benefit ratios to compare competing alternatives. Park et al. [8] examined the safety effect of wider edge lines by analyzing crash frequency data for road segments with and without wider edge lines based on different statistical approaches. Their results showed positive safety effects of wider edge lines installed on rural, two-lane highways. Lyon et al. [9, 10] and Moreno et al. [11] incorporated the Empirical Bayes method to determine the safety effectiveness of installing left-turn lanes and obtained operational effectiveness of passing zones from passing frequency. Their results indicated that these were cost-effective treatments for two-lane rural highways. Yuan et al. [12], Yuan and Lu [13], and Montella and Mauriello [14] used the Empirical Bayesian method and Safety Indexes to evaluate safety benefits and suggest relevant improvements for highway intersections. Cruzado and Donnell [15] evaluated the effectiveness of dynamic speed display signs in transition zones of two-lane, rural highways, and the results indicated that signs were effective in reducing free-flow passenger car operating speeds. There are many methods of evaluating the effectiveness of special improvements. The Bayes methods are widely used and effective. Li and Washburn [16] presented an improved methodology for two-lane highway facility analysis and a new version of CORSIM with the capability of modeling two-lane highways. Zhu et al. [17] discussed the relationship among drivers' heart rates, variability of the vehicle in the running process, design speed consistency, operating speed coordination, speed reduction coefficients, and speed gradients in two-lane highways. Persaud et al. [18], Mujalli and De Oña [19], and Vlahogianni and Golias [20] used the Empirical Bayes and Bayesian Network method to estimate the safety of specific sites and analyze the injury severity of traffic accidents. Wu et al. [21] developed two Mixed Logit models based on crash data collected in New Mexico to analyze driver injury severities in SV and MV crashes on rural two-lane highways.

In this study, the HSEP research findings are presented to evaluate the engineering solutions and their effectiveness in reducing traffic crash severities on Highway G109 in Beijing, China. The potential causal factors were identified based on the proposed evaluation criteria, and primary countermeasures were developed against inferior driving conditions. Six cost-effective engineering solutions were specifically implemented to improve two-lane highway safety conditions: (1) traffic sign replacement, (2) repainting of pavement markings, (3) installation of roadside barriers, (4) intersection channelization, (5) drainage optimization, and (6) sight distance improvement. An Empirical Bayes (EB) model-based before-after study was conducted. The results indicate that the proposed engineering solutions effectively improved traffic safety performance by significantly reducing crash occurrence risks and crash severities.

2. Data Collection

G109 highway is a major corridor connecting the city of Beijing and the province of Hebei with a length of 119.2 kilometers. The two-lane highway system is comprised mostly of Class 2, Class 3, and Class 4 highway segments. The terrain conditions are mainly mountainous with some plains and hills along the highway. All traffic engineering solutions for G109 were designed and finished in 2004.

Detailed crash data for G109 were collected from the traffic accident database of the Beijing Traffic Management Bureau (2000–2008), and part of the minor accident data was gathered from the Beijing Municipal Roadway Administration Bureau. Traffic volume data and geometric data were obtained from the Annual National Highways Traffic Volume Statistical Handbook (2000–2008) and the Design Documents of G109 managed by the Transport Planning and Research Institute of the Ministry of Transport, China, respectively. Accident and traffic volume data for similar segments were obtained from the Traffic Police Corps of Guangxi Department of Public Security (2004-2005).

3. Engineering Treatments Implemented

3.1. Criteria for Development of Crash Hotspot Identification. HSEP mainly uses traffic engineering treatments to improve or eliminate potential crash hotspots to enhance traffic safety on highways. This is different from highway reconstruction and extension projects and aims to rehabilitate and improve traffic facilities. The objectives of HSEP are to decrease traffic accident fatality rates, especially in serious accidents and to supply a better highway traffic and safety environment with safer facilities. HSEP targets to maximize safety benefits with the lowest cost, least amount of engineering, and least time.

Assessments were first conducted due to limited construction funds. Five aspects of geometric features and roadway characteristics were chosen, including the horizontal curve radius and longitudinal gradient. Detailed assessment criteria information is shown in Table 4.

3.2. Engineering Treatments Implemented. Based on the design documents of G109, all latent dangerous entities were identified following the above judgment criteria and accident data. A total of 612 traffic signs were installed or replaced; 27,000 m^2 of pavement markings were painted; 15,137 m of barriers were built or replaced; 8 intersections were channelized. The average cost to implement these changes was only 100,713 RMB per kilometer.

3.2.1. Traffic Signs. The problems with the traffic sign system before treatment were discontinuous signs, lack of warning signs, mistakes on locations and content of signs, occlusion problems, and too many characters on a tourism sign.

Based on the existing problems and characteristics of the highway curvatures and gradients, new traffic signs were designed and installed systematically to avoid redundant information. Furthermore, locations of different signs were established according to the operation speed of traffic flow and sight distance.

In total, 612 new traffic signs were installed, including 19 solar energy signs. Several oversized warning signs and indication signs with high visibility were fixed as reminders to reduce speed and drive carefully before segments of curves and slopes. Relevant solar horizontal induction signs and flat top tubular delineators and chevron signs were set up at borders of the roadside along curves with the combination of median delineators. In addition, more easily recognized guide signs and tourist spot signs replaced older signs along the entire highway. Finally, stop and yield signs were installed on minor road approaches.

3.2.2. Pavement Markings. More than 27,000 m^2 of pavement markings were painted, including 1,400 m^2 of special pavement markings.

Night performance pavement markings such as yellow lane-lines and white edge-lines were painted at general segments. Channelizing lines, word markings, crosswalks, and symbol markings were introduced at the intersections. Thin red lines were painted in the vertical direction of sharp curves or accident prone locations. Optical illusion deceleration markings were painted at lane borders to remind drivers of special geometric conditions and at lane mediums for pedestrians.

3.2.3. Roadside Barriers. Almost 20% of accidents were Run-off-road (ROR) crashes along the highway. Thus, 15,137 m of barriers were built or replaced according to the degree of roadside hazard, accident frequency, operation speed, traffic volume and composition, and landscape demand in several special segments along the highway. The forgiveness design principle was one of the most critical methods we followed. However, because of terrain conditions, barrier equipment was essential in certain circumstances.

A total of 2,850 m of high strength concrete barriers were cemented beside cliff edges at segments of small, continuous horizontal curves and areas with a high frequency of side collision accidents. Serrated concrete barriers with a light appearance for guidance were built at sharp horizontal curve segments with fewer crashes.

A total of 5,158 m of corrugated beam barriers or steel guardrails were installed at cliff segments, winrows, and high retaining walls without enough earth pressure outside of the shoulder. A-level corrugated beam barriers were chosen for downgraded sections with higher operation speeds and serious consequences of rollover accidents. B-level barriers were prepared for upgraded sections with a lower possibility of crashes.

A total of 7,129 m of cable barriers were placed at sections of landscape with enough clearance and earth pressure outside of the shoulder. Yellow reflectors were pasted on barriers to enhance their visibility. A-level protection barriers were implemented at sections with rollover accident records or higher risk coefficients, and B-level cable barriers were used to protect areas without crash records or roadside shallows.

Figure 1: Warning signs and pavement markings.

3.2.4. Intersection Channelization. There were many 3-legged and 4-legged intersections along the highway. There were previously no channelization pavement markings, and vehicles operated without rules. Many of these intersections had poor visibility, so the frequency of frontal and side collisions was much higher in these areas than in others (Figure 2).

Therefore, (1) channelization pavement markings were painted to split different direction flows and standardize traffic order; (2) stop signs and/or yield signs were placed at minor-legged roads according to highway classes and traffic volumes for clearer priority and fewer conflicts; (3) a left-turn pocket lane was created within the confines of an existing roadway; (4) several solar yellow flashing lights were added to enhance night safety for vehicles, pedestrians and cyclists. As a result, 8 main intersections were channelized and the others were modified with stop or yield signs.

3.2.5. Drainage Optimization. The highway side ditch in G109 was in the shape of a rectangle with a wide cross section and deep depth of 40 to 50 centimeters. This type of side ditch was a latent conflict and had the potential to aggravate the severity of ROR crashes.

According to the real terrain conditions and roadside qualifications, the side ditch was transformed into a flat butterfly side ditch at several special segments to reduce the severity of ROR crashes.

3.2.6. Sight Distance Improvement. Poor visibility problems were serious on G109, especially at segments of intersections, switch-backs, and sharp curves. Slope flattening is an effective way to improve road visibility. Therefore, buildings, structures, mounds, trees, or wire poles were removed at sight triangles of intersections or at the inner sides of horizontal curves in some circumstances. This increased the visibility of convex mirrors, warning signs, and pavement markings (Figure 1).

3.2.7. Other Implementations. In addition to the treatments described, there were other significant implementations. For instance, roadside improvement, scenic view platform treatment, and tunnel management were extensively implemented along G109.

Table 1: Statistics of accidents and traffic volumes of G109, Beijing.

Durations	Total accidents	Minor accidents	General accidents	Major accidents	Deaths	Injuries	Traffic volumes
2000.5–2001.4	103	33	63	7	8	61	2,708
2001.5–2002.4	160	109	42	9	10	70	2,358
2002.5–2003.4	173	126	32	15	15	61	2,090
2003.5–2004.4	289	239	46	4	4	110	2,222
2004.5–2005.4	431	417	13	1	1	27	2,830
2007.5–2008.4	519	503	10	6	6	175	3,420

Figure 2: Intersection channelization.

4. Safety Effects of Treatments

4.1. Empirical Bayes Analysis. Few resources have been devoted to evaluation in the literature. In this study, the safety effects of the treatments were evaluated by the Empirical Bayes (EB) before-after analysis based on the severity of traffic accidents. In the EB estimate, the joint use of two clues is implemented by a weighted average, that is,

$$m = w \cdot x + (1 - w) \cdot P,$$
$$\sigma(m) = \sqrt{(1 - w) \cdot m}, \tag{1}$$

where m is an estimate of expected accidents; x is the number of accidents expected on similar segments; P is the number of accidents on G109; w is the weight and $\sigma(m)$ is the standard deviation of m. Consider

$$x = \mu l,$$
$$w = \frac{1}{1 + (\mu \cdot Y)/\varphi}, \tag{2}$$

where μ is the safety performance function, the average number of accidents/(km-year); l is the length of the segment, km; Y is the number of years during which the accident count materialized; φ is the overdispersion parameter.

Here, the Safety Performance Function (SPF) was an equation of the Average Daily Traffic (ADT) and length of the segment. Consider

$$\mu = a \times \mathrm{ADT}^{b}, \tag{3}$$

where a, b are regression parameters.

After regression analysis with general and major accident data and the ADT data in Tables 1 and 3, two regression parameters were obtained, $a = 0.0073$ and $b = 0.5146$. Then, $\mu = 0.436$ for 2004 to 2005 and $\mu = 0.481$ for 2007 to 2008 were computed. The resulting weights were 0.82 and 0.81, meaning that 52.13 and 57.46 accidents were expected on similar segments, respectively. Finally, the average estimates of expected accidents were 45.27 ± 2.85 and 49.58 ± 3.07 accidents. There were only 14 and 16 accidents that occurred on G109 in Beijing, showing a significant improvement in safety after implementation of the engineering treatments.

4.2. Accident Severity Analysis after Treatment Implementation. The number of minor accidents increased quickly. Possible reasons for this may be increased traffic volume, a better traffic environment causing relaxed driver vigilance, and a gradually improved accident record system. Figure 5 shows the variations of accident count versus traffic volume before and after the engineering treatments.

Accident severity analysis was evaluated in detail to find the safety effect evidence of engineering treatment effectiveness after implementation. Detailed information is listed in Table 5.

Six fatal accidents and 8 major accidents were caused by driver factors, totaling 100 percent of such accidents. All fatal accidents and one half of the major accidents occurred during the daytime. All fatal accidents and 5 major accidents occurred during clear weather conditions. This suggests that highway factors, such as sight distance, pavement condition, and geometric features were not the main causes of these types of accident. This indirectly proves the effectiveness of the treatments (Table 2).

ROR accidents occupied 32.18% of the total number of accidents, with 1 fatal and 1 major accident occurring. This indicates that most vehicles involved in ROR accidents were protected by treatments such as drainage optimization, shoulder improvements, and clear zone improvements (Figures 3 and 4).

Truck and tractors had higher crash incidence rates. The majority of accidents included one or two vehicles and were frontal or side collisions. No fatal or major accidents occurred at intersection areas. Drivers over the age of 54 and female drivers were safer. Driver violations, carelessness, and false estimation of motor performance were the main causes of driver error.

These results suggest that the engineering treatments played a role in protecting lives from serious crashes and reduced crash severity.

Table 2: Geometric features of G109, Beijing.

Design indexes	Units	Class 2	Class 3
Lane	—	2	2
Section	—	Origin to K28 + 560	K28 + 560 to destination
Design speed	km/h	60	30
Paving width	m	12.0	8.5
Shoulder width	m	0.5	0.5
Length	km	119.15	
The minimum horizontal curve radius	m	10 (<60 m, 209 segments)	
The maximum longitudinal gradient	%	9.49 (>5%, 87 segments)	

Table 3: Statistics of accident data and ADT in similar segments.

Highway segments	Length/km	ADT		General and major accidents	
		2004	2005	2004	2005
G207	331.171	3,906	4,618	164	246
G209	520.258	3,058	3,236	245	303
G210	250.377	4,356	4,593	126	175
G321	375.709	3,308	3,190	122	141
G322	554.348	5,716	6,330	354	452
G323	712.332	5,804	6,779	289	310
G324	714.561	10,116	11,930	705	788
G325	244.731	2,928	3,217	90	109

Figure 3: Drainage optimization.

Figure 4: Roadside shoulder improvements.

5. Conclusions

HSEP is a cost-effective traffic safety improvement project initialized by the Ministry of Transport, China. Various engineering treatments were implemented. Safety effects were evaluated using EB-based before-after studies, and crash severity was analyzed using the data collected from the G109 highway in Beijing. The major contributions of this study to the state of the practice include the following.

(1) Traffic crash data and traffic dynamic data were collected to support EB-based before-after studies and crash severity analyses.

(2) All potential crash hotspots were identified according to the proposed assessment criteria, which included

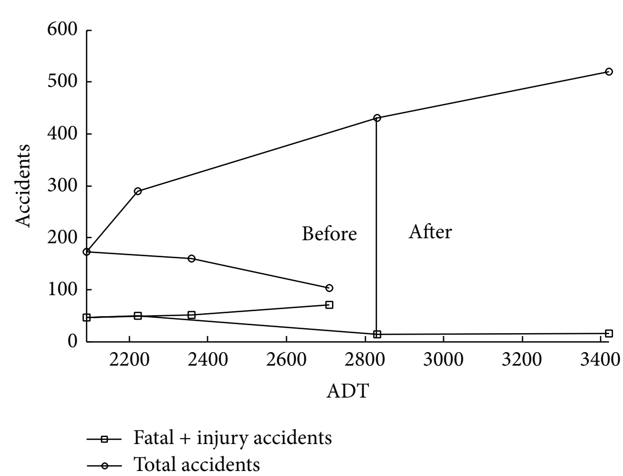

Figure 5: Traffic accidents versus traffic volume of G109, Beijing.

Table 4: Assessment criteria for potential crash hotspots on G109, Beijing.

Categories	Indexes	Units	Class 2	Class 3
Sharp curve	The horizontal curve radius	m	$R \leq 125$	$R \leq 60$
Heavy gradient	The longitudinal gradient	%	$I \geq 6.0$	$I \geq 7.0$
Continuous downgrade	The longitudinal gradient	%	$I \geq 4.5$ (≥3 km)	$I \geq 5$ (≥3 km)
Bad sight distance	Decision sight distance	m	$L \leq 150$	$L \leq 80$
Bad clear zone	The height of slope	m	$H \geq 4.0$	
	The distance to shoulder border		$W \leq 3.0$ (Lakes, rivers, swamps, ditches)	

Table 5: Variables, values, and actual classification by severity (2007-2008).

Variables	Categories	Coding/values	Total	Fatality	Major injury	Minor injury	Property damage
			519 (100%)	6 (1.16%)	8 (1.54%)	98 (18.88%)	407 (78.42%)
1	Driver's gender	Man = 1	498 (95.95%)	6 (1.20%)	7 (1.41%)	95 (19.08%)	390 (78.31%)
		Woman = 2	21 (4.05%)	0 (0.00%)	1 (4.76%)	3 (14.29%)	17 (80.95%)
2	Driver's age	<25 = 1	38 (7.32%)	1 (2.63%)	1 (2.63%)	7 (18.42%)	29 (76.32%)
		25~34 = 2	154 (29.67%)	3 (1.95%)	3 (1.95%)	38 (24.68%)	110 (71.42%)
		35~44 = 3	125 (24.08%)	1 (0.80%)	2 (1.60%)	32 (25.60%)	90 (72.00%)
		45~54 = 4	61 (11.76%)	1 (1.64%)	1 (1.64%)	17 (27.87%)	42 (68.85%)
		>54 = 5	141 (27.17%)	0 (0.00%)	1 (0.71%)	4 (2.84%)	136 (96.45%)
3	Type of vehicle	Passenger car = 1	220 (42.38%)	1 (0.45%)	2 (0.91%)	39 (17.73%)	178 (80.91%)
		Bus = 2	4 (0.77%)	0 (0.00%)	0 (0.00%)	0 (0.00%)	4 (100.00%)
		Light truck = 3	18 (3.47%)	0 (0.00%)	0 (0.00%)	2 (11.11%)	16 (88.89%)
		Truck = 4	231 (44.52%)	4 (1.73%)	1 (0.43%)	45 (19.48%)	181 (78.36%)
		Tractor trailer = 5	6 (1.16%)	0 (0.00%)	2 (33.33%)	2 (33.33%)	2 (33.33%)
		Tractor = 6	36 (6.94%)	1 (2.78%)	2 (5.56%)	10 (27.78%)	23 (63.88%)
		Cycles = 7	4 (0.77%)	0 (0.00%)	1 (25.00%)	0 (0.00%)	3 (75.00%)
4	Vehicle involved	1 = 1	162 (31.21%)	2 (1.23%)	1 (0.62%)	26 (16.05%)	133 (82.10%)
		2 = 2	340 (65.51%)	3 (0.88%)	6 (1.76%)	69 (20.29%)	262 (77.07%)
		>2 = 3	17 (3.28%)	1 (5.88%)	1 (5.88%)	3 (17.65%)	12 (70.59%)
5	Weather condition	Clear = 1	377 (72.63%)	6 (1.59%)	5 (1.33%)	73 (19.36%)	293 (77.72%)
		Cloudy = 2	78 (15.03%)	0 (0.00%)	1 (1.28%)	13 (16.67%)	64 (82.05%)
		Rainy = 3	58 (11.18%)	0 (0.00%)	2 (3.45%)	11 (18.97%)	45 (77.58%)
		Snowy = 4	6 (1.16%)	0 (0.00%)	0 (0.00%)	1 (16.67%)	5 (83.33%)
6	Month	Spring = 1	63 (12.14%)	0 (0.00%)	0 (0.00%)	0 (0.00%)	63 (100.00%)
		Summer = 2	144 (27.75%)	1 (0.69%)	3 (2.08%)	30 (20.83%)	110 (76.40%)
		Autumn = 3	154 (29.67%)	2 (1.30%)	2 (1.30%)	30 (19.48%)	120 (77.92%)
		Winter = 4	158 (30.44%)	3 (1.90%)	3 (1.90%)	38 (24.05%)	114 (72.15%)
7	Crash time	0~5 = 1	51 (9.83%)	0 (0.00%)	2 (3.92%)	9 (17.65%)	40 (78.43%)
		6~11 = 2	189 (36.42%)	3 (1.59%)	1 (0.53%)	37 (19.58%)	148 (78.30%)
		12~17 = 3	187 (36.02%)	3 (1.60%)	3 (1.60%)	38 (20.33%)	143 (76.47%)
		18~23 = 4	92 (17.73%)	0 (0.00%)	2 (2.17%)	14 (15.22%)	76 (82.61%)
8	Crash type	Frontal collision = 1	139 (26.78%)	3 (2.16%)	2 (1.44%)	38 (27.34%)	96 (69.06%)
		Side collision = 2	37 (7.13%)	0 (0.00%)	4 (10.81%)	4 (10.81%)	29 (78.38%)
		Rear-end collision = 3	74 (14.26%)	1 (1.35%)	0 (0.00%)	9 (12.16%)	64 (86.49%)
		Scape = 4	102 (19.65%)	1 (0.98%)	1 (0.98%)	21 (20.59%)	79 (77.45%)
		Run-off-road = 5	167 (32.18%)	1 (0.60%)	1 (0.60%)	26 (15.57%)	139 (83.23%)
9	Cause	Driver factors = 1	480 (92.48%)	6 (1.25%)	8 (1.67%)	89 (18.54%)	377 (78.54%)
		Vehicle factors = 2	10 (1.93%)	0 (0.00%)	0 (0.00%)	1 (10.00%)	9 (90.00%)
		Environment factors = 3	29 (5.59%)	0 (0.00%)	0 (0.00%)	8 (27.59%)	21 (72.41%)

sharp curves, heavy gradients, continuous downgrades, insufficient sight distance, and vague clear zones.

(3) Seven categories of engineering improvements for enhanced safety were implemented: traffic signs, pavement markings, roadside barriers, intersection channelization, drainage optimization, sight distance improvement, and other treatments.

(4) An evaluation of the safety effects of completed treatments was conducted. The EB-based before-after method and the crash severity analysis indicated that the proposed engineering treatments had significant effects on enhancing safety.

Conflict of Interests

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

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