MODELING DRIVER DISTANCE RECOGNITION AND SPEED PERCEPTION AT NIGHT FOR FREEWAY SPEED LIMIT SELECTION IN CHINA

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ABSTRACT

Developing a proper speed limit for freeway is critical for roadway safety. Due to the difference in visibility between day and night, it is necessary to have different speed limits for the two time periods on freeways with changing geometric features. Aiming to reduce the number of crashes caused by speeding at night on freeways, an exploratory study was conducted on the maximum speed limit at night. In order to investigate the potential relationship between drivers' distance recognition and driving speed and between speed perception and driving speed under different geometric design features, an experiment was carried out on a 22-km-long freeway segment on Chang-song freeway in China. Based on round-trips made by 10 drivers during day and night on this segment, drivers' recognition distance (distance between a sign and the location where the sign was clearly recognized the first time) and estimated speed were recorded. The data analysis results show that driver recognition distance at night decreases by about 7% compared with recognition distance at daytime. The accuracy of driver speed perception at nighttime is only 29%, whereas it is 67% at daytime. With the collected data, several multivariate non-linear regression models were established to capture the relationship among the variables of recognition distance, estimated speed at night, driving speed, and highway alignment indexes. Then the modeling results were used to develop the speed limit model by physical equations. A case study is introduced at the end of the paper.

Keywords: Freeway, traffic safety, nighttime, recognition distance, estimated speed, maximum speed limit.

1 INTRODUCTION

Being a relatively new type of highway to most drivers in China, crashes on Chinese freeways are closely related to high speed. Setting proper speed limit at night has been realized as a potential crash countermeasure for freeways in China. The different visibility between day and night necessitates for different speed limits on freeways. Understanding the impact of night visibility on driver's visual recognition ability and speed estimation has been an interesting study subject for many years. Related references are listed in Table 1.

In summary, in an earlier study on driver's distance recognition, the impacts of lighting and speed were considered. However, as an important influence factor, highway alignment was neglected. On the other hand, in another study on driver's estimated speed, only its deviation was analyzed statistically or the influence factors of deviation were analyzed qualitatively, but the changing rule of driver's speed perception was not given quantitatively and corresponding models were not established. Considering the difference in driving behavior among different countries, particularly between developed countries and developing countries, it is important to investigate how drivers' performance is affected by freeway design elements and driving speed to develop a proper nighttime speed limit. The purpose of the project was to study how to properly develop freeway maximum speed limit at night based on driver's distance recognition and speed perception under different highway design features and driving speeds. The paper can give a contribution to existing knowledge, but the results are still those of an exploratory study.

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Table 1: Related references.

No.	Authors and year	Features of the research
1	Konstantopoulos *et al.*, 2010 [1]	Low visibility decreased the validity of driver's visual search at night.
2	Easa *et al.*, 2010 [2]	Improved lighting was helpful for boosting driver's visual recognition ability to traffic sign on straight section.
3	Babizhayev *et al.*, 2009 [3]	Glare affected driving characteristics greatly with the increasing age of drivers.
4	Hua & Donnell, 2010 [4]	Establishing driver's acceleration and deceleration models on rural highway at night.
5	Horberry *et al.*, 2006 [5]	Enhanced traffic sign was advantageous to drivers at night.
6	Baker, 1999 [6]	Drivers tend to underestimate their driving speed under limited light conditions at night.
7	Campbell *et al.*, 2010 [7]	If drivers underestimate or overestimate their travel speed, they will travel faster or slower than they expect.
8	Suh *et al.*, 2006 [8]	Limited lighting condition at night made drivers feel that they were driving slowly, because of which they would accelerate, resulting in speeding.
9	Henriette *et al.*, 2009 [9]	Drivers' speed perception in countries with a low accident rate was more accurate than that in countries with a high accident rate.
10	Pasetto & Manganaro, 2009 [10]	Drivers decreased speed stably at daytime, but driver's speed perception was not stable at night.
11	Mannering, 2009 [11]	Drivers' perception to speeding was affected by their age, sex, and nationality greatly.

2 EXPERIMENTS DESIGN

A segment on Chang-Song freeway with a design speed of 100 km/h connecting the cities of Chang-Chun and Song-Yuan was selected for the experiment. This 22-km-long freeway segment was divided into 18 sections based on the geometric design features, particularly, the horizontal curves and slopes. Table 2 lists the classification of experimental section.

Ten non-professional drivers with 3–10 years of driving experience participated in this experiment. Each driver was required to abstain from drugs and alcohol during the experiment. Smoking and cell phone were not allowed. The experiment time was set at 9:00 to 11:00 for daytime and 21:00 to 23:00 for nighttime. Each driver drove six round-trips on this segment at both daytime and nighttime in the same car with six different speeds, i.e. 70 km/h, 80 km/h, 90 km/h, 100 km/h, 110 km/h, and 120 km/h. There are 42 traffic signs along this segment.

Once the vehicle reached the desired speed v, the designated on-board passage would record the time when the driver recognized a sign ahead as t_1 and again record the time t_2 as the vehicle passing by the sign. A stopwatch was used to record the timing. At the same time, drivers were requested not to see the speedometer and to report his estimated speed value, which was also recorded. Thus, each driver's recognition distance S was calculated as below:

$$S = v \times (t_2 - t_1) \tag{1}$$

Table 2: Classification of experimental section.

Longitudinal Slope i (%)	Horizontal curve radius R (m)			
	$0 \le R \le 700$	$700 < R \le 4000$	$4000 < R \le 10000$	$R > 10000$
$0 \le i \le 2$	Curve with little radius	Curve with medium radius	Curve with large radius	Flat and straight section
$2 < i \le 4$	Curve slope with a small radius	Curve slope with a medium radius	Curve slope with a large radius	Straight and slope section

Table 3: Average recognition distance at daytime and nighttime.

Driving speed (km/h) / Recognition distance (m) / Alignment	At daytime						At night					
	70	80	90	100	110	120	70	80	90	100	110	120
Curve with little radius	378	341	321	305	299	295	291	282	280	269	263	258
Curve slope with medium radius	361	334	318	313	279	289	313	302	291	276	269	270
Curve with medium radius	470	427	372	359	331	324	327	321	318	279	261	261
Curve slope with large radius	403	382	359	330	321	312	361	358	338	305	301	286
Curve with large radius	496	432	415	371	330	327	358	349	331	313	286	284
Straight and slope section	417	391	356	327	313	303	446	433	418	366	331	303
Flat and straight section	455	423	409	350	345	323	462	450	423	373	356	319

3 DRIVER DISTANCE RECOGNITION

3.1 Between daytime and nighttime

Total number of data samples is 2520, including 240 data sets on curve with small radius, 120 data sets on curve slope with medium radius, 840 data sets on curve with medium radius, 120 data sets on curve slope with large radius, 600 data sets on curve with large radius, 120 data sets on straight and slope section, and 480 data sets on flat and straight sections. However, curve slope with small radius has no observations. The average recognition distances at different driving speed and alignment during daytime and nighttime are summarized in Table 3.

As shown in Table 2, driver recognition distance at night decreases by about 7% compared with recognition distance at daytime. Driver's recognition distance increases with the decrease of driving speed at both daytime and nighttime. There is also a clear pattern of driving recognition distance versus the alignment type.

3.2 Recognition distance at night

Driver's recognition distance at night varies with driving speed, horizontal curve radius, and longitudinal slope. The distribution of recognition distance versus driving speed at night is illustrated in Fig. 1. As shown in Fig. 1, as driving speed increases, recognition distance decreases.

The distribution of recognition distance versus horizontal curve radius at night is illustrated in Fig. 2. From Fig. 2, it is clear that, with the increase of horizontal curve radius, recognition distance at night also increases, so does the standard error.

The distribution of recognition distance versus longitudinal slope at night is illustrated in Fig. 3. As expected, using the car's headlight recognition distance is at a maximum when

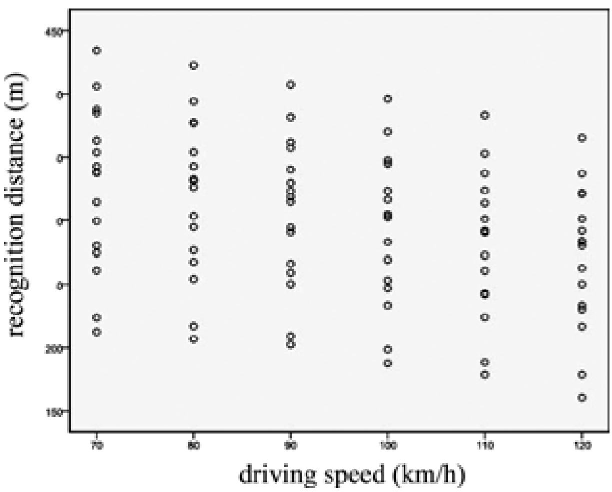

Figure 1: Distribution of recognition distance versus driving speed at night.

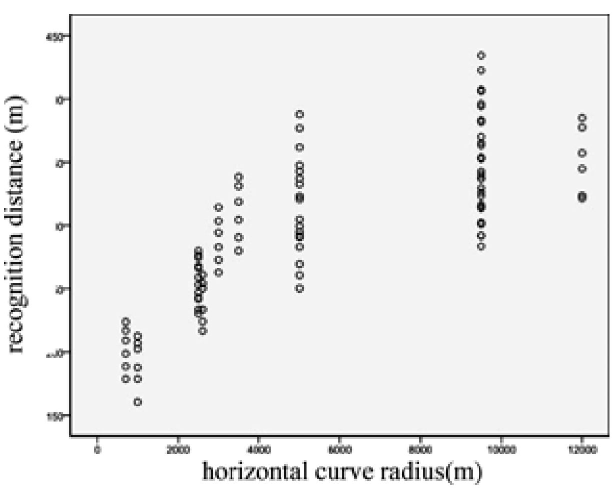

Figure 2: Distribution of recognition distance versus horizontal curve radius at night.

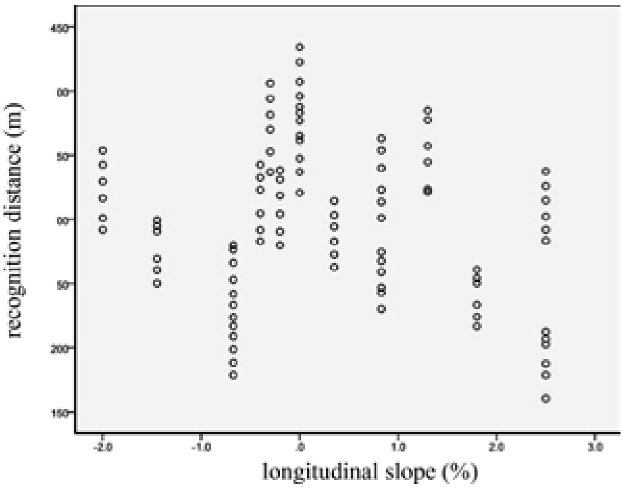

Figure 3: Distribution of recognition distance versus longitudinal slope at night.

vertical slope is zero or close to zero. It reduces in uphill segment and increases, after a dip at 0.5% slope, at downhill segment at night.

3.3 Modeling recognition distance

The preliminary results show the potential relationship between recognition distance and other variables. Different functional forms were explored with SPSS (Statistical Product and Service Solution) program with results listed in Table 4. SPSS is among the most widely used programs for statistical analysis.

The following model has the highest R^2 of 0.983; thus, it is considered to be the best model to determine the relationship.

$$S = -1.15v + 57.8\ln R + 80.54e^{-1.72i} - 104 \tag{2}$$

where, S is the driver's identification distance, m; v is the driving speed, km/h; R is the horizontal curve radius, m; and i is the longitudinal slope.

4 DRIVER SPEED PERCEPTION

4.1 Between daytime and nighttime

Another interesting result from this study is the driver speed perception. During each experiment run, the on-board passenger asked the drivers to estimate their driving speed. Average driver's estimated speed data are listed in Table 5.

The results in Table 4 show that generally there is a gap between actual driving speed and drivers' estimated speed. The gap varies depending on other factors investigated in this study. During the daytime, driving speed is almost the same as estimated speed when driving speed is 70 and 80 km/h. At nighttime, drivers tend to underestimate the driving speed when driving speed is less than 90 km/h, and overestimate when the driving speed is more than 100 km/h. Drivers tend to overestimate the speed at curves with small radius both

Table 4: Nighttime recognition distance models.

No.	Relation models	a	b	c	d	k	R^2
1	$S = a \times v + b \times R + c \times i + k$	–1.15	0.014	–34.8	—	366	0.916
2	$S = a \times v + b \times R + c \times e^{d \times i} + k$	–1.15	0.013	97.5	–1.59	298	0.968
3	$S = a \times v + b \times e^{c \times R} + d \times i + k$	–1.15	3.25E5	0.00	–34.8	–3.24E5	0.918
4	$S = a \times v + b \times \ln R + c \times i + k$	–1.15	60.3	–27.9	—	–68.8	0.942
5	$S = a \times v + b \times \ln R + c \times e^{d \times i} + k$	–1.15	57.8	80.5	–1.72	–104	0.983
6	$S = a \times v + b \times R^c + d \times i + k$	–1.15	17.5	0.299	–30.1	218	0.952
7	$S = a \times \ln v + b \times R + c \times i + k$	106	0.014	–34.8	—	739	0.917
8	$S = a \times \ln v + b \times R + c \times e^{d \times i} + k$	–106	0.013	97.5	–1.59	671	0.966
9	$S = a \times \ln v + b \times e^{c \times R} + d \times i + k$	–106	3.36E5	0.00	–34.8	–3.36E5	0.917
10	$S = a \times \ln v + b \times \ln R + c \times i + k$	–106	60.3	–27.9	—	305	0.941
11	$S = a \times \ln v + b \times \ln R + c \times e^{d \times i} + k$	–106	57.8	80.5	–1.71	269	0.981
12	$S = a \times \ln v + b \times R^c + d \times i + k$	–106	17.5	0.299	–30.1	591	0.951
13	$S = a \times e^{b \times v} + c \times R + d \times i + k$	–143	0.005	0.014	–34.8	487	0.919
14	$S = a \times e^{b \times v} + c \times \ln R + d \times i + k$	–143	0.055	60.3	–27.9	51.9	0.942
15	$S = a \times v^b + c \times R + d \times i + k$	–0.079	1.50	0.014	–34.8	331	0.919
16	$S = a \times v^b + c \times \ln R + d \times i + k$	–0.079	1.50	60.3	–27.9	–104	0.942

during the daytime and during the nighttime. The driver's speed estimation versus actual speed is shown in Fig. 4.

It is clear that driver estimated speeds deviated more at nighttime compared with that at daytime.

4.2 Estimated speed at night

The gap between driver estimated speed at night and horizontal curve radius at different driving speed is illustrated in Fig. 5, which shows that drivers' estimated speed varies differently from driving speed by horizontal curve radius.

When driving speed ranges from 70 km/h to 90 km/h, the gaps are not noticeable. When driving speed ranges from 100 km/h to 120 km/h, drivers' estimated speed decreases with increasing horizontal curve radius.

Drivers' estimated speed versus longitudinal slope corresponding to different driving speeds is shown in Fig. 6.

It can be found that the drivers' estimated speed varies randomly with the increasing longitudinal slope. According to the regression analysis, there is a weak relationship between the estimated speed and longitudinal slope at night.

4.3 Modeling drivers' estimated speed

According to the above analysis, various models were developed to best capture the relationship between drivers' estimated speed and actual driving speed and horizontal curve radius. All models explored are given in Table 6.

Table 5: Diver estimated speed under different speed and highway alignment.

Driving speed (km/h) / Estimated speed (km/h) / Alignment	At daytime						At night					
	70	80	90	100	110	120	70	80	90	100	110	120
Curve with little radius	70	80	100	110	120	130	70	70	95	110	130	140
Curve slope with medium radius	70	80	90	95	115	125	60	80	90	110	130	130
Curve with medium radius	70	80	90	100	110	120	60	75	90	100	125	130
Curve slope with large radius	70	80	92	100	110	120	60	75	85	105	120	125
Curve with large radius	70	78	90	100	110	115	60	70	85	100	120	120
Straight and slope section	70	80	90	100	105	110	60	70	80	105	110	120
Flat and straight section	70	80	90	100	100	110	60	70	80	100	110	120

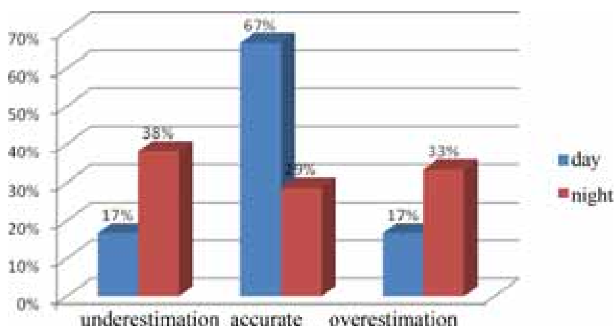

Figure 4: Accuracy of driver speed perception.

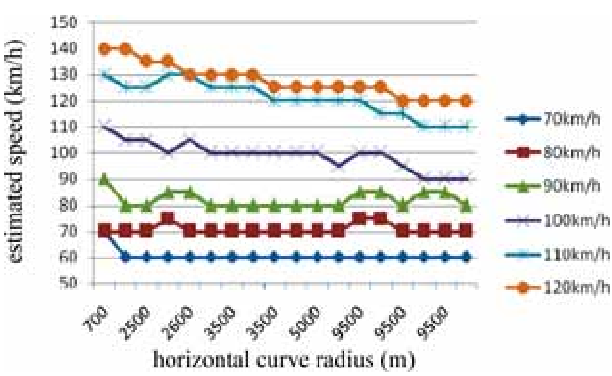

Figure 5: Driver estimated speed versus horizontal curve radius.

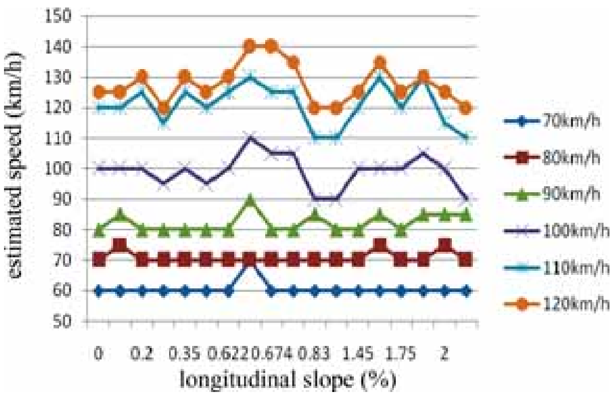

Figure 6: Driver estimated speed versus longitudinal slope.

Table 6: Driver estimated speed models at night.

	Relation models	a	b	c	k	R^2
1	$v_p = a \times v + b \times R + k$	1.47	−0.001	—	38.5	0.959
2	$v_p = a \times v + b \times \ln R + k$	1.44	−4.20	—	−7.77	0.962
3	$v_p = a \times v + b \times e^{c \times R} + k$	1.44	−11437	0.000	11398	0.960
4	$v_p = a \times \ln v + b \times R + k$	133	−0.001	—	−503	0.946
5	$v_p = a \times \ln v + b \times \ln R + k$	133	−4.20	—	−473	0.949
6	$v_p = a \times \ln v + b \times e^{c \times R} + k$	133	−10326	0.000	9823	0.946
7	$v_p = a \times e^{b \times v} + c \times R + k$	159	0.005	−0.001	−169	0.960
8	$v_p = a \times e^{b \times v} + c \times \ln R + k$	159	0.005	−4.20	−138	0.959

The best model with a highest R^2 of 0.962 algorithms is given below:

$$v_p = 1.44v - 4.2 \ln R - 7.77 \tag{3}$$

where, v_p is the driver estimated speed at night, km/h.

5 MAXIMUM SPEED LIMIT AT NIGHT

For safety, driver recognition distance needs to satisfy eqn (4).

$$S \geq ST \tag{4}$$

where, S_T is the stopping sight distance and is composed of three parts which are shown in eqn (5).

$$S_T = S_1 + S_2 + S_0 = \frac{v}{3.6}t + \frac{v^2}{254(\varphi + i)} + S_0 \tag{5}$$

where, S_1 is the driving distance during driver's reaction time, m; S_2 is braking distance, m; S_0 is safe distance, m; t is driver's reaction time, s; φ is pavement's friction coefficient.

Combining eqns (2), (4), and (5), we get:

$$\frac{v^2}{254(\varphi+i)}+1.844v+109-57.8\ln R-80.54e^{-1.72i}\leq 0 \tag{6}$$

Thus, the theoretical maximum speed limit on freeway at night can be obtained below:

$$v_{\mathrm{lt}}=\left(\sqrt{0.85-\frac{109-57.8\ln R-80.54e^{-1.72i}}{254(\varphi+i)}}-0.922\right)\times 254\times(\varphi+i) \tag{7}$$

where, v_{lt} is the theoretical maximum speed limit value on freeway at night, km/h. φ in eqn (6) can be taken as 0.3, with the pavement being wet and speed being 120 km/h. Moreover, considering the load of all the driving wheels of the car accounting for 50% to 65% of total weight, φ can be multiplied by 0.5 according to the most adverse condition.

According to above analysis, affected by highway alignment and speed, driver speed perception will produce deviation. Therefore, it is necessary to correct theoretical maximum speed limit on freeway at night. According to eqn (3), driver estimated speed deviation can be calculated by eqn (8).

$$\Delta v=v_{\mathrm{lt}}-\frac{1}{1.44}(v_{\mathrm{lt}}+4.2\ln R+7.77) \tag{8}$$

where, Δv is the correction value of theoretical maximum speed limit value on freeway at night, km.

Thus, the corrected theoretical maximum speed limit value on freeway at night can be expressed by:

$$v_{\mathrm{lc}}=v_{\mathrm{lt}}+\Delta v \tag{9}$$

where, v_{lc} is the corrected theoretical maximum speed limit value on freeway at night, km/h.

Taking new-constructed section of Chang-Song freeway as example, the maximum speed limit on freeway at night was calculated as listed in Table 7.

6 CONCLUSIONS

The results can be summarized below:

1. Driver recognition distance at daytime is more than that at night, and it decreases with an increase in the driving speed and longitudinal slope; and increases with an increase in the horizontal curve radius. The modeling results show that there is a negative linear, positive logarithm, negative exponent relationship between the driver recognition distance at night and driving speed, horizontal curve radius, and longitudinal slope, respectively.
2. Driver speed perception is less accurate at night, and at daytime, it is accurate at low speed and deviated at high speed. At night, drivers tend to underestimate speed at low speed and overestimate speed at high speed. There is no relationship between driver estimated speed and longitudinal slope at night. Established model shows that there is a positive linear, negative logarithm relationship between driver estimated speed at night and driving speed and horizontal curve radius, respectively.
3. Based on driver recognition distance and stopping sight distance, a method to calculate was given to obtain maximum speed limit value on freeway at night.

Table 7: Corrected theoretical maximum speed limit value at night on Chang-Song freeway.

No.	Pile No.	i (%)	R (m)	v_{lc} (km/h)	No.	Pile No.	i (%)	R (m)	v_{lc} (km/h)
1	K582 + 636 ~ K583 + 090	0.238	1000	91	21	K594 + 350 ~ K595 + 300	+0.126	2600	99
2	K583 + 090 ~ K583 + 500	2.2	1000	97	22	K595 + 300 ~ K595 + 900	−1.375	2600	94
3	K583 + 500 ~ K583 + 940	−2.5	1000	82	23	K595 + 900 ~ K596 + 475	+1.800	2600	104
4	K583 + 940 ~ K584 + 228	−2.5	+∞	98	24	K596 + 475 ~ K597 + 100	−1.501	2600	93
5	K584 + 228 ~ K585 + 200	0.000	700	87	25	K597 + 100 ~ K597 + 440	+0.229	2600	99
6	K585 + 200 ~ K585 + 430	−0.674	700	85	26	K597 + 440 ~ K598 + 600	+0.229	5000	104
7	K585 + 430 ~ K586 + 200	−0.674	2500	96	27	K598 + 600 ~ K599 + 192	−0.200	5000	103
8	K586 + 200 ~ K586 + 737	+0.830	2500	101	28	K599 + 192 ~ K599 + 900	−0.200	+∞	108
9	K586 + 737 ~ K587 + 350	+0.830	9500	111	29	K599 + 900 ~ K600 + 500	−1.150	+∞	104
10	K587 + 350 ~ K587 + 950	+0.250	9500	109	30	K600 + 500 ~ K600 + 750	1.300	+∞	113
11	K587 + 950 ~ K588 + 750	−2.000	9500	100	31	K600 + 750 ~ K600 + 982	1.300	+∞	113
12	K588 + 750 ~ K589 + 350	−0.300	9500	107	32	K600 + 982 ~ K601 + 350	−0.200	3500	100
13	K589 + 350 ~ K590 + 615	0.000	9500	108	33	K601 + 350 ~ K601 + 750	1.750	3500	107
14	K590 + 615 ~ K590 + 850	0.000	5000	103	34	K601 + 750 ~ K602 + 250	−0.430	3500	99
15	K590 + 850 ~ K591 + 450	−1.450	5000	98	35	K602 + 250 ~ K603 + 200	0.800	3500	103
16	K591 + 450 ~ K592 + 017	−0.400	3000	98	36	K603 + 200 ~ K603 + 750	1.800	3500	107
17	K592 + 017 ~ K592 + 400	−0.400	3000	98	37	K603 + 750 ~ K603 + 958	−0.622	3500	99
18	K592 + 400 ~ K593 + 604	+0.350	2600	100	38	K603 + 958 ~ K604 + 200	−0.622	+∞	106
19	K593 + 604 ~ K593 + 800	+0.350	2600	100	39	K604 + 200 ~ K604 + 500	0.177	+∞	109
20	K593 + 800 ~ K594 + 350	+1.500	2600	103					

It is worth emphasizing that this paper is an initial research and requires further study to achieve a higher degree of efficiency. Implications of results need further investigation.

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