A study on capacity of signalized intersection under snow-ice conditions based on classical model modification

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Received 1 February 2014, www.tsi.lv

Abstract

As the common climatic phenomena frequently occurring in northern China in winter, snow and ice weathers have made great influence to the capacity of signalized intersection. By starting from snow and ice conditions, this paper makes improved correction about the calculation of capacity of signalized intersection respectively based on HCM Method and Method of Stopping Line. On the basis of HCM Method, the author comprehensively considers factors influencing the capacity of signalized intersection under snow and ice conditions, and calibrates the integrated parameters influencing the capacity of signalized intersection under snow and ice conditions; grounded on Method of Stopping Line, the author then calibrates various parameters and makes classified study about each parameter separately according to snow weather and freezing condition, finally giving out parameter values under various states. With the help of the revised model, the paper calculates the capacity of signalized intersection and then makes the comparison between traffic capacities under various snow and ice conditions and that with capacity of signalized intersection under normal weather, hence with strong practical significance.

Keywords: Snow and ice conditions; Signalized intersection; capacity; Parameter modification; Comparative analysis

1 Introduction

With the progress of society, people have put forward higher requirements for traffic network, especially the service level of intersection and the adaptability to changes in sudden traffic problems. Under snow and ice conditions, the friction coefficient on pavement/road surface decreases and the running speed of vehicles also reduces, both of which not only lower the capacity of road and aggravate traffic congestion, but also especially easily form the chain crowding effect, thus causing local congestion in road network. Under this circumstance, it can effectively relieve problems of traffic jam and declining capacity under snow and ice weathers and thus displays very practical significance for lowering occurrences of traffic accidents under snow and ice conditions to study the traffic situation of signalized intersection in traffic network, grasp its real service level and to take various effective measures about traffic management and control as well as induction.

At present, domestic scholars have proposed various methods to calculate the capacity of signalized intersection under adverse environments and the most typical is the method of reducing coefficient put forward in American Highway Capacity Manual [1]. Based on previous studies, such scholars as Mr.Zhang regard the feeling of drivers as main evaluation criterion under snow-ice conditions and then they integrate this with such factors as road operating capacity, traffic security coefficient and outside wealth condition, where delay, control, weather and etc. are main factors influencing the capacity of signalized intersection under snow and ice weathers [2]. Lida and other scholars design the model with relative intensity quantization process to visualize feelings of drivers, and with the assistance of computer programs, it can vividly describe the process of drivers forming judgments in signalized intersection and their psychological anxiety changes, hence determining the service level of signalized intersection with this as the evaluation criterion [3]. With grey theory system as research basis, other scholars like Li establish the evaluation model with five important indicators like stopping delay and queuing length, and then evaluate the capacity of signalized intersection and its running state based on this model [4]. Such scholars as Peeheux, Zhang and Flannery further study comprehensive evaluation indices for motor vehicle service level in signalized intersection and design the evaluation index system based on this [5-7]. After collecting data about friction coefficient in different pavements with snow and ice and analysing the braking response time and braking length for drivers to start, stop vehicle on road with snow and ice and to make a turn at intersection, Cheng Guozhu and other scholars finally take the sedan car as example to give out the suggestive value for maximum speed ensuring safe traffic on pavement covered with snow and ice, thus calculating the capacity of signalized intersection under snow and ice conditions based on this

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[8]. To sum up, domestic studies about the capacity of signalized intersection under snow and ice conditions have not yet been mature, which is mainly because the psychological feelings and driving fatigue of drivers are difficult for quantitative research [9-10].

2 Modelling method

The capacity of intersection refers to the sum of vehicles that can pass each in-lane at intersection in unit time, and the model for capacity of intersection under snow and ice conditions is based on the capacity of signalized intersection under normal weather. After revising its value, the paper finally obtains the capacity of signalized intersection under snow and ice weathers, and the author then makes further research about this with HCM Method and Method of Stopping Line.

2.1 HCM METHOD

After analysing and systemizing lots of data and referring to the achievements of previous scholars, the paper gives the model to calculate the saturation flow rate of intersection lane under snow and ice conditions on the ground of HCM Method, which is shown in Formula 1 as follows:

$$S_{snow-ice} = f_{snow-ic1i} \times S = f_{snow-ice1} \cdot N \cdot f_w \cdot f_{HV} \cdot f_g \cdot f_p \cdot f_{bb} \cdot f_a \cdot f_{LU} \cdot f_{LT} \cdot f_{RT} \cdot f_{Lpb} \cdot f_{Rpb} \cdot S_0 . \quad (1)$$

In the formula, $f_{snow-ice1}$ is the correction coefficient of saturation flow rate under snow and ice conditions.

According to Formula 1, when it comes to calculating the saturation flow rate of each lane, firstly, the paper needs to select the ideal theoretical saturation flow rate S0. Generally speaking, each straight-going lane selects 1,650pcu/h while each left-turning and right-turning lane both select 1,550pcu/h. Then, the author makes various corrections about the value according to the influencing factors.

After determining the saturation flow rate of lane, the author sums the saturation flow rate of each single in-lane so as to obtain the capacity of intersection. Under snow and ice conditions, the calculation formula for capacity of each land group $C_{snow-icei}$ is shown in Formula 2 as follows.

$$C_{snow-icei} = S_{snow-icei} \times \lambda_i . \quad (2)$$

In the formula, λ_i is the green-time-rate (the effective green time/signal cycle length);

$S_{snow-icei}$ is the saturation flow rate of lane or lane group i.

Then the capacity of the whole intersection is shown in the following Formula 3.

$$C_{snow-ice} = \sum_i C_{snow-icei} . \quad (3)$$

In conclusion, in order to determine the capacity of signalized intersection under snow and ice conditions, the paper also needs to make clear the correction coefficient on snow and ice pavement $f_{snow-ic1i}$ for the coefficient is influenced by several factors and it is also complicated. As a result, the author will make detailed research about the correction coefficient of saturation flow rate under snow and ice weathers in the next section.

2.2 METHOD OF STOPPING LINE

According to the road traffic flow situation in China, the author also needs to regard the stop line as control section when calculating the capacity of intersection controlled by computer signal; in other words, whether it involves with left turn, right turn or straight going, as long as the vehicle passes the stop line in effective green time, it can be deemed as entering and passing the intersection. Under snow and ice conditions, the method to calculate the capacity of intersection based on Method of Stopping Line is listed as follows:

(1) Capacity of one straight-going lane

$$C_S = f_{snow-ice2} \frac{3600}{T} \left(\frac{t_g - t_0}{t_i} + 1 \right) . \quad (4)$$

In the formula, T is the cycle of signal light, which takes value according to the actual signal cycle.

C_S is the design capacity of one straight-going lane, (with the unit of) veh/h.

tg is the green time in a signal cycle, s.

t0 is the time for the first vehicle to start and pass the stop line after the green signal light is on, s, which averagely takes the value of 2.3s under normal weather.

ti is the average time headway for straight-going vehicles to pass the stop line, s.

(2) Capacity of special right-turning lane

$$C_r = f_{snow-ice2} \frac{3600}{t_r} , \quad (5)$$

t_r is the average interval time for two successive cars to continuously pass the stop line, s.

(3) Capacity of special left-turning lane

$$C_l = f_{snow-ice2} \frac{3600}{t_l} , \quad (6)$$

t_l is the average interval time for two successive cars to continuously pass the stop line, s.

(4) Capacity of straight-going and left-turning mixed driving lane

$$C_{Sl} = C_l\left(1 - \frac{3}{4}\beta_l\right) f_{snow\text{-}ice\,2}\,. \tag{7}$$

In the formula, βl is the proportion of vehicles to turn left in this mixed driving lane.

(5) Capacity of straight-going and right-turning mixed driving lane

$$C_{Sr} = C_r\left(1 - \frac{1}{2}\beta_l\right) f_{snow\text{-}ice\,2}\,. \tag{8}$$

In the formula, βr is the proportion of vehicles to turn right in this mixed driving lane.

According to the definition of signalized intersection, the capacity of signalized intersection which is obtained on the basis of Method of Stopping Line is listed as follows:

$$C = \sum_{i=1}^{4}\left(\sum_{j=1}^{m_s} C_{sij} + \sum_{j=1}^{m_l} C_{lij} + \sum_{j=1}^{m_r} C_{rij} + \sum_{j=1}^{m_{sl}} C_{slij} + \sum_{j=1}^{m_{sr}} C_{srij}\right). \tag{9}$$

In the formula, ms, mr, ml, msl and msr respectively represent the number of straight-going lane, special left-turning lane, special right-turning lane, straight-left lane and straight-right one.

Based on the cross-shaped intersection and Method of Stopping Line, by analysing and systemizing mass data, and referring to the achievements of previous researches, the paper revises it according to various influencing factors in snow and ice weathers and then gives out the model to calculate the saturation flow rate of intersection lane under snow and ice conditions. To sum up, in order to determine the capacity of signalized intersection under snow and ice conditions, the author should also make clear the correction coefficient on snow and ice pavement $f_{snow\text{-}ice\,2}$ for the coefficient is influenced by several factors and it is also very complicated. In consequence, the paper will make detailed research about the correction coefficient of saturation flow rate under snow and ice weathers in the next section.

3 Parameter modification

3.1 DETERMINATION OF INFLUENCING FACTOR $f_{snow\text{-}ice\,1}$ UNDER SNOW AND ICE CONDITIONS ACCORDING TO HCM METHOD

The above part makes separate study about various factors influencing the capacity of signalized intersection under snow-ice. However, the capacity of signalized intersection under snow and ice conditions actually results from the influence of several factors, whose functions cannot be expressed by their simple product; therefore, the paper needs to consider various factors and establishes the comprehensive correction coefficient influencing the capacity of intersection under snow and ice conditions. In details, the correction coefficient of saturation flow rate under snow and ice $f_{snow\text{-}ice\,1}$ is mainly influenced by weather condition wea, lane number La, lane width W and lane function Lc. Thereinto, the worse the weather condition is, the smaller the correction coefficient of saturation flow rate (is); the larger the values of lane number, lane width and lane function are, the bigger the correction coefficient of saturation flow rate. As a result, the model for correction coefficient of saturation flow rate is established in Formula 10 as follows according to Gravity Model.

$$f_{snow\text{-}ice\,1} = k\,\frac{L_c^b \times W^c \times La^d}{Wea^a}\,. \tag{10}$$

In the formula, a, b, c, d and k are respectively undetermined parameters.

In order to simplify the calculation process, the model is changed into linear one for treatment and the logarithm is taken towards both sides of the equal sign to obtain the following Formula 11.

$$\ln f_{snow\text{-}ice\,1} + a\ln Wea = \ln k + b\ln L_c + c\ln W + d\ln La \tag{11}$$

According to the definition, when the value of weather influencing factor Wea is 0, the value of $f_{snow\text{-}ice\,1}$ is 1, which means that weather factor exerts no influence to saturation flow rate. In other words, it takes the value equal to the saturation flow rate under normal conditions. Then, the paper calibrates it according to the data in field measurement and makes linear regression towards Formula 11, finally obtaining a=1.02, b=0. 3 4, c=0.69, d=-0.74, k=0.83 and linear fitting R2=0.672. This shows that that correction model of saturation flow rate can better explain the influence of various factors to the capacity of signalized intersection under snow and ice conditions, which is shown in Formula 12 as follows.

$$f_{snow\text{-}ice\,2} = \begin{cases} 0.83 \times \dfrac{L_c 0.34 \times W^{0.69} \times La^{0.74}}{Wea^{1.02}}, & Wea \neq 0 \\ 1 & Wea = 0 \end{cases}. \tag{12}$$

3.2 DETERMINATION OF INFLUENCING FACTOR $f_{snow\text{-}ice\,2}$ UNDER SNOW AND ICE CONDITIONS ACCORDING TO METHOD OF STOPPING LINE

As there are differences between Method of Stopping Line and HCM Method in calculation method, their coefficients under snow and ice weathers are totally different. Based on calibrating correction parameters in the model to calculate capacity according to HCM Method, the paper should also need to recalibrate corrected parameters in the capacity model based on Method of Stopping Line, for better representing the capacity of signalized intersection under snow and ice weathers.

Under snow and ice conditions, the frictions that the vehicle suffers in going straight and turning are different, which causes its acceleration of starting and braking are also different. Therefore, when calibrating these parameters, the author also needs to distinguish vehicles turning from those going straight for separate calibration. After making measurement and calculation for several times, the paper obtains calibration results of correction parameters based on Method of Stopping Line under the condition of snow and ice pavement, which is listed in Table 1 as follows.

TABLE 1 Parameter Calibration Results in Parking Line Method under Snow-Ice

Weather	Turning right	Going straight	Turning left
Normal weather	1.0	1.0	1.0
Light snow	0.74	0.78	0.73
Moderate snow	0.52	0.61	0.55
Heavy snow	0.46	0.56	0.49
Snowstorm	0.39	0.48	0.41
Road surface covered with snow	0.64	0.74	0.66
Rough road surface with ice	0.55	0.64	0.57
Smooth road surface with ice	0.50	0.54	0.48
Mixed road surface with snow and ice	0.38	0.45	0.40

Nowadays, there is rare situation where mixed driving lanes, straight-left or straight-right, exist in signalized intersection; therefore, when simulating regression, it can be ignored. According to Table 2-5, in the model based on Method of Stopping Line, snow and ice weathers exert very large influence to the capacity of road and the biggest impact can reach about 60 percent. Thereinto, the influence of straight-going lane is relatively small; left-turning lane takes the second place and the influence of right-turning lane is the biggest, which is also related with the radius of vehicles turning circle in signalized intersection. In other words, the bigger the radius is, the smaller the influence is. Furthermore, the radius of turning circle in straight-going lane approaches infinite; consequently, snow and ice weathers exert the smallest impact to it; the left-turning lane takes the second place. As the radius of turning circle in right-turning lane is the smallest, snow and ice weathers thus exert the biggest influence to it.

3.3 MODEL CALCULATION RESULT AND COMPARISON

In order to determine the precision of models previously calibrated for capacity of signalized intersection under snow and ice conditions, the paper now selects the typical “cross-shaped” intersection for investigation, then concludes and systemizes survey data for verification calculation. Then the paper makes calculation according to the data about traffic volume at the intersection between Huaihe Road and Songshan Road. Thereinto, Songshan Road-Huaihe Road is the intersection between primary and secondary trunk roads in Harbin City; furthermore, the former possesses 8 two-way lanes, so does the latter. The place of intersection in-lane is broadened to 5 lanes. As the signal control, cycle time is 134s and the signal-timing phase is 4-phase timing, thereinto the phase of green light for going straight in south-north direction is 35s and that in east-west direction is 25s. As the left-turnings in east-west direction and south-north direction separately set up independent phases, the green light time is respectively 20s and 25s, and the yellow light time for going straight and turning left is separately 8s and 9s; right turning is not restricted by the signal light.

When the snow and ice condition is rough road surface with ice, two models are employed to respectively calculate the capacity of the intersection of Songshan Road-Huaihe Road, which are shown in Table 2. The result of model calculation is slightly smaller than that corrected from practical observation data. This is because when the signal light is yellow, the vehicles actually entering the intersection can still continue to pass the intersection; however, the model fails to calculate the capacity in this time.

TABLE 2 Result of the Intersection of *Songshan Road-Huaihe Road* about Capacity (HCM)

	Model calculation (pcu/h)	Corrected result from actual measurement (pcu/h)	Deviation
East in-lane	2039	2203	7.44%
South in-lane	1598	1782	10.33%
West in-lane	1994	2178	8.45%
North in-lane	1537	1639	6.22%

TABLE 3 Result of the Intersection of *Songshan Road-Huaihe Road* about Capacity (Method of Stopping Line)

	Model calculation (pcu/h)	Corrected result from actual measurement (pcu/h)	Deviation
East in-lane	2146	2203	2.59%
South in-lane	1673	1782	6.12%
West in-lane	2146	2178	1.47%
North in-lane	1673	1639	2.07%

According to Table 2, the difference between the result of model calculation and that of actual measurement is not large and the maximum deviation is no more than 11 percent. Therefore, the model is considered to better reflect the capacity of signalized intersection on rough road surface with snow and ice. The difference between the result of model calculation and that of actual measurement in Table 2 is not large and the maximum deviation is 12 percent. As a result, it can better reflect the capacity of each in-lane in signalized intersection on rough road surface with snow and ice.

By comparing the results from these two methods, the paper finds that the result calculated on the basis of Stopping Line Method is ablest to reflect the capacity of intersection, and the average deviations of intersections at Songshan Road-Huaihe Road is 3.30 percent. The difference between the result calculated on the ground of HCM Method and the capacity obtained from actual measurement is the largest, and the average deviations in these two intersections separately reach 9.29 percent and 8.11 percent, far higher than the result obtained on the basis of Stopping Line Method. This is because the traffic flow composition of urban roads in China is complicated and the type of vehicle is various. Furthermore, the result obtained on rough road surface with ice exactly reflects the application scope of method to calculate capacity. According to the above two models, the traffic capacities of various in-lanes under various climatic conditions at intersections Songshan Road-Huaihe Road and Hongqi Street-Huaihe Road are respectively obtained from calculation and then the paper makes comparison between the result from model calculation with data in actual measurement. And the result shown in Table 4 is the result obtained on the basis of Stopping Line Method.

According to Table 4, snow and ice weathers generate obvious influence to the capacity of signalized intersection. In actual measured values, from normal weather to mixed road surface with snow and ice, the capacity of intersection has reduced by nearly 40 percent, which means that it is quite necessary to study the capacity of signalized intersection under snow and ice conditions. What's more, there is deviation between the result from model calculation established on the basis of Stopping Line Method and that from field measurement. However, the deviation keeps within the range from -7% to 12%; therefore, it is considered that the model can better represent the capacity of various in-lanes in signalized intersection under snow and ice conditions. In the end, the capacity of the whole intersection is calculated through that of each in-lane, whose result is shown in Table 5.

According to Table 5, under various weathers, the deviation between the value of model calculation and that from field observation is not large; moreover, the maximum deviation is 4.84 percent and the minimum one is 0.32 percent. This shows that the model can perfectly reflect the capacity of signalized intersection. For example, under the condition of mixed road surface with snow and ice, the traffic capacities of two intersections studied by the paper are both 6,624pcu/h in model calculation while the traffic capacities from actual observation are separately 6,477pcu/h and 6,500pcu/h. Hence, the deviation between calculated value and values in field observation are both within 200pcu/h, and the deviation ratios is separately 2.27 percent and 1.91 percent.

TABLE 4 Result of the Intersection In-lanes Capacity in Ice-snow (Method of Stopping Line)

Weather	**In-lane**	***Songshan Road-Huaihe Road***		
		Model calculation (pcu/h)	**Corrected result from actual measurement (pcu/h)**	**Deviation**
Normal weather	East in-lane	2325	2381	2.35%
	South in-lane	1824	1859	1.88%
	West in-lane	2325	2368	1.82%
	North in-lane	1824	1798	-1.45%
Road surface with snow	East in-lane	2248	2295	2.05%
	South in-lane	1615	1822	11.36%
	West in-lane	2248	2264	0.71%
	North in-lane	1615	1738	7.08%
Rough road surface with ice	East in-lane	2146	2203	2.59%
	South in-lane	1673	1782	6.12%
	West in-lane	2146	2178	1.47%
	North in-lane	1673	1639	-2.07%
Smooth road surface with ice	East in-lane	2058	2108	2.37%
	South in-lane	1602	1627	1.54%
	West in-lane	2058	1986	-3.63%
	North in-lane	1602	1576	-1.65%
Mixed road surface with snow and ice	East in-lane	1853	1845	-0.43%
	South in-lane	1459	1439	-1.39%
	West in-lane	1853	1814	-2.15%
	North in-lane	1459	1379	-5.80%

TABLE 5 The Capacity of Signalized intersection in Ice-snow of *Songshan Road–Huaihe Road* and *Hongqi Street-Huaihe Road* (Method of Stopping Line)

Weather	***Songshan Road–Huaihe Road***		
	Model calculation (pcu/h)	**Corrected result from actual measurement (pcu/h)**	**Deviation**
Normal weather	8298	8406	-1.28%
Road surface with snow	7726	8119	-4.84%
Rough road surface with ice	7638	7802	-2.10%
Smooth road surface with ice	7320	7297	0.32%
Mixed road surface with snow and ice	6624	6477	2.27%

In order to show that Method of Stopping Line can better reflect the capacity of signalized intersection under snow and ice conditions, the paper now makes comparison between the calculated results based on HCM Method and Conflict Point Method with the result based on Method of Stopping Line, and the results are shown in Table 6. According to Table 6, in terms of the intersection at Songshan Road-Huaihe Road, there are errors with varying degrees between the results calculated from two models and the result in actual measurement. Thereinto, the deviation between the result obtained on the basis of HCM Method and data in actual measurement is the biggest, which approaches 7 percent; the deviation between model result based on Method of Stopping Line and data in actual measurement is the smallest. However, the result is too large, which is because when the red signal light is on, the headstocks of some vehicles have surpassed the stop line, thus making the model result too large. Longitudinally speaking, the error between the results from these two methods is the biggest on road surface with snow. This means that light snow exerts the largest influence to the capacity of signalized intersection. When snow and ice weathers change to road surface with ice, the error between the result of model calculation and that in actual measurement only changes a little, which means that as snow and ice weathers change, the influence to capacity of signalized intersection mainly reflects in aspects from normal weather to road surface with snow, which is the same to the change scope of friction coefficient on road surface.

TABLE 6 The Capacity of Signalized intersection in Ice-snow

Weather	*Songshan Road-Huaihe Road*				
	Model calculation (pcu/h)		**Corrected result from actual measurement (pcu/h)**	**Deviation**	
	Based on HCM Method	Based on Stopping Line Method		Based on HCM Method	Based on Stopping Line Method
Normal weather	8177	8298	8406	2.72%	-1.28%
Road surface with snow	7568	7726	8119	6.79%	-4.84%
Rough road surface with ice	7425	7638	7802	4.83%	-2.10%
Smooth road surface with ice	7107	7320	7297	2.60%	0.32%
Mixed road surface with snow and ice	6326	6624	6477	2.33%	2.27%

4 Conclusion

With snow and ice conditions as starting point, the paper calculates the traffic capacities of signalized intersection under various snow and ice conditions. Based on these two models, the author respectively calculates the traffic capacities of the whole signalized intersection at Songshan Road-Huaihe Road and at Songshan Road-Huaihe Road and he then compares the results with data in actual measurement. The results show that: compared with HCM Method, Method of Stopping Line possesses a smaller error with results in actual measurement, whose maximum deviation ratio is no more than 12 percent. Finally, it is considered that the capacity model based on Method of Stopping Line can well reflect the actual situation.

However, the action of taking the cross-shaped intersection for example in the study is slightly one-sided; therefore, in the future researches, the author needs to introduce the intersections in other types to make further study about the capacity of intersection under snow and ice conditions.

Acknowledgements

This work was financially supported by Jilin Province Science and Technology Development Project (20120747).

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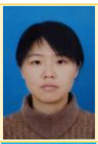

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