Study on Methods to Calculate Visibility on Blowing Snow

Masaru Matsuzawa[1], Masao Takeuchi[2]

[1]Civil Engineering Research Institute of Hokkaido
Hiragishi 1-3, Toyohira-ku, Sapporo 062-8602, Hokkaido JAPAN
E-mail:masaru@ceri.go.jp
[2]Japan Weather Association, Hokkaido Branch
Nishi 23, Kita 4, Chuo-ku, Sapporo 064-8555, Hokkaido JAPAN

Abstract

Information on the occurrence of blowing snow is useful in enabling drivers to select safer and more appropriate routes. Visibility meters have been used to measure the intensity of blowing snow on roads. However, the area covered by the presently installed visibility meters is too limited to obtain region-wide information on blowing snow. This led us to seek methods of estimating the intensity of blowing snow using wind velocity, snowfall intensity and other parameters, all of which are obtained relatively easily. First, based on past studies on mass flux of snow (Mf) and visibility (Vis), we established that log(Vis) = -0.773 log(Mf) + 2.845 for visibility up to 3000 m. Considering that mass flux of snow is snow concentration multiplied by wind velocity, we then attempted to establish methods to estimate snow concentration. For this, two conditions were examined to estimate snow concentration using wind velocity and snowfall intensity. In one condition, the wind velocity at 10 m above the ground was 8.5 m/s or greater and the temperature was less than -2 ℃; in the other condition, the wind velocity at 10 m above the ground was less than 8.5 m/s or the temperature was -2 ℃ or higher. The visibility estimated using related equations agreed closely with the measured visibility, which indicates that our visibility estimation methods can be applied to region-wide monitoring of blowing snow on roads.

1. Introduction

Visual information is essential to road traffic safety. In cold, snowy regions, however, access to useful visual information can become impaired (poor visibility) due to snowfall or blowing snow, sometimes making driving impossible. Poor-visibility- induced traffic accidents are tending to involve ever-greater numbers of cars, such as in the 186-car pileup that occurred in blowing snow on the Do'ou Expressway in Chitose City, Hokkaido, on March 17, 1992. The accident left 2 dead and 73 with various degrees of injury, making it the worst multi-vehicle accident in Japan.

In Japan, visibility meters have been used to measure poor visibility. The areas covered by the currently installed meters, however, are too limited to obtain region-wide information regarding blowing snow occurrence. But the intensity of blowing snow depends heavily on wind velocity and snowfall intensity, and region-wide data of both these parameters can be readily collected by ground-based meteorological stations and weather radar.

In other words, if the intensity of blowing snow and related poor visibility can be estimated using data on wind velocity and snowfall intensity, use of that information can enhance the safety of winter driving. Visibility figures themselves need not be presented in order to maintain winter road traffic. A five-stage visibility scale (＜ 50 m, 50 - 200 m, 200 - 500 m, 500 - 1000 m, ≧ 1000 m) is considered sufficient for practical use.

Our study, summarized herein, aimed at establishing methods of estimating visibility by using meteorological data that are available relatively easily and methods of using that information to understand and forecast current and future region-wide distribution of blowing snow.

2. Methods of estimating visibility in the suspension layer

The three types of motion for blowing snow particles are shown in Figure 1: rolling, saltation, and suspension (Takeuchi, 1984). Rolling particles are few and can be regarded as part of saltation particles. Saltation is predominant at 0.01 - 0.1 m above the ground. At the upper boundary of this layer, saltation particles begin to suspend. Thus, there is suspension layer above the saltation layer that is predominated by suspension particles. Visibility on roads is typically represented by that at a height of 1.2 m above the ground, the viewpoint of small-vehicle drivers. In this paper, blowing snow particles are those belonging to the suspension layer unless otherwise stated.

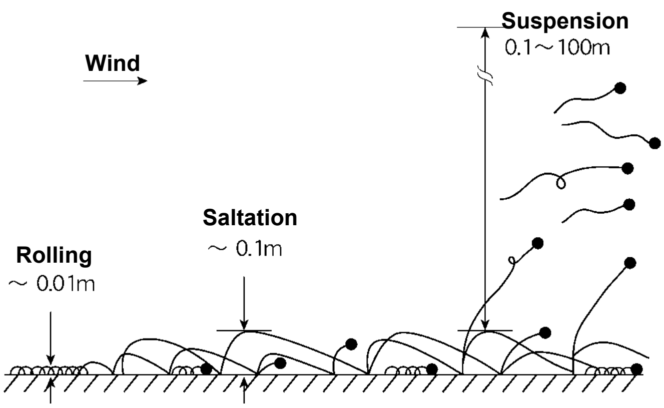

Figure 1: Different types of blowing snow motion (Takeuchi, 1984)

2.1 Relationship between visibility and mass flux of snow

The intensity of blowing snow can be expressed as a physical quantity, using snow concentration N (mass of airborne snow in a unit space) and mass flux of snow Mf (mass of airborne snow passing through a unit area per unit time). These two physical quantities have the following relationship.

$$Mf = N \cdot V \quad (1)$$

where V: wind velocity

The relationship between visibility Vis and mass flux of snow Mf has been studied by Mellor (1966), Saito (1971), Budd et al. (1966), and Takeuchi et al. (1975). Takeuchi and

Fukuzawa (1976) collated the results of these studies and clarified the relationship between visibility and mass flux of snow (Figure 2). As indicated in the graph, log(Vis) can be approximated using a linear equation of log(Mf), up to the visibility of 3000 m. Above 3000 m, measured values begin to deviate from the approximation line. However, as the influence of visibility of 3000 m or more on road traffic is negligible, the relationship between visibility and mass flux of snow can be described using the following approximation.

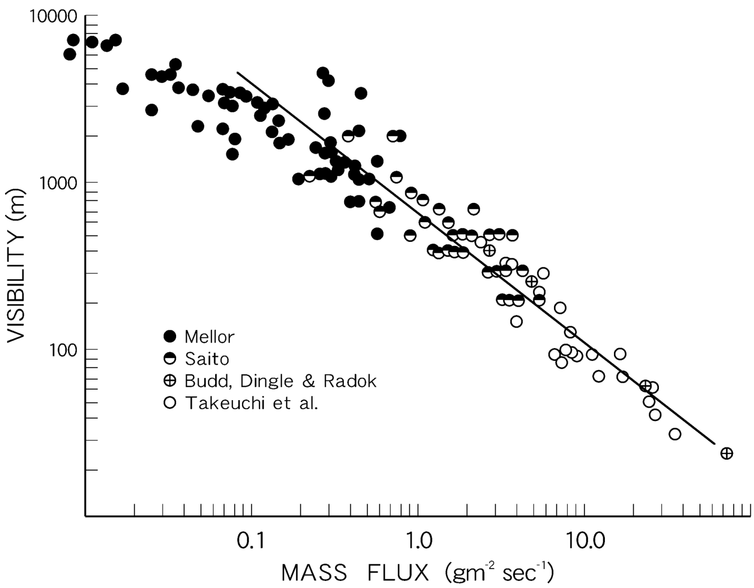

Figure 2: Relationship between visibility and mass flux of snow. They can be linearly approximated. (Takeuchi and Fukuzawa, 1976)

$$log(Vis)= -0.773\ log(Mf)+2.845 \tag{2}$$

2.2 Vertical distribution equation describing snow concentration

Equations (1) and (2) suggest that snow concentration N and wind velocity V need to be obtained in order to find visibility. It is easy to measure wind velocity, but not snow concentration. This led us to seek methods of obtaining snow concentration using readily available meteorological data.

Snow concentration in floating layers can be obtained by solving turbulent diffusion equations, as described below (Takeuchi and Matsuzawa, 1991).

$$N(Z) = \frac{P}{w} + \left(N_t - \frac{P}{w}\right)\left(\frac{Z}{Z_t}\right)^{-\frac{w}{kU_*}} \tag{3}$$

where N(Z): snow concentration at height Z; Nt: snow concentration at the reference height of Zt; w: falling velocity of airborne snow particles (a constant); P: snowfall intensity; k: Karman's constant (0.4), and U_*: friction velocity.

The first term (P/w) in Equation (3) can be regarded as the concentration of snowfall-supplied airborne snow particles (hereinafter: snowfall particles). The second term (Nt - P/w) is snow concentration at height Zt minus the concentration of snowfall particles, in other words, the concentration of drifting-snow-supplied airborne snow particles (hereinafter: suspension particles) at height Zt.

While w is a constant in Equation (3), in blowing snow accompanied by snowfall it is assumed that snowfall particles of relatively larger diameters are mixed with suspension particles of relatively smaller diameters.

Hence, let us examine the following model, which relates to suspension particles accompanied by snowfall. Assuming that snowfall particles and suspension particles do not interact with each other, Equation (3) can be rewritten as follows.

$$N(Z) = \frac{P}{w_f} + \left(N_t - \frac{P}{w_f} \right) \left(\frac{Z}{Z_t} \right)^{-\frac{w_b}{kU_*}} \tag{4}$$

where w_f: falling velocity of snowfall particles, w_b: falling velocity of drifting particles.

2.3 Calculation methods for snow concentration

Snowfall intensity P in Equation (4) is available relatively easily from meteorological radar and/or ground stations. However, it is not easy to obtain real-time measurements of the falling velocity of drifting particles w_b, the falling velocity of snowfall particles w_f, the snow concentration at Zt (Nt), and the friction velocity U_*. Because we sought to establish methods of estimating visibility using meteorological data that are readily available, we investigated these values using the results of previous studies.

Previous theoretical calculations, laboratory experiments, and field observations presented typical falling velocities of snowfall and drifting particles. Budd (1964) measured the falling velocity of airborne snow particles and found that wb = 0.3 - 0.38 m/s at a height of 0.125 m. Based on this, wb = 0.35 m/s was used for the calculations of snow concentration, as described later. For the falling velocity of snowfall particles, wf = 1.2 m/s was used, which Ishizaka (1995) obtained in his detailed study by measuring snowflakes with fewer cloud particles.

The reference height Zt is typically set at the height of the boundary between saltation layer and suspension layer. Based on the results of observation by Takeuchi (1981), Zt = 0.15 m was used for the calculations described hereinafter.

Next we examined the snow concentration Nt at the reference height Zt. It is not easy to measure actual snow concentration. For prompting drivers to exercise caution, it is most practical to make calculations for cases of the worst visibility. The observation by Takeuchi et al. (1975) in Hokkaido and Takeuchi (1981) in the US that the snow concentration at a height of 0.15 m is approximately 1.0 - 30 g/m^3. Based on this, Zt = 0.15 m and Nt = 30 g/m^3 were used for the calculations described later.

Friction velocity U* and roughness constant Z_o have the following relationship.

$$V_z = \frac{U_*}{k} \ln\left(\frac{Z}{Z_0}\right) \tag{5}$$

where V_z: wind velocity at a given height Z. Substituting $Z_o = 1.5 \times 10^{-4}$ (m) and k = 0.4, both presented by Nishio and Ishida (1973), into Equation (5) and using V_{10} for a height of 10m, friction velocity can be described as

$$U_* = 0.036 \cdot V_{10} \tag{6}$$

Substituting w_b, w_f, Nt, and U*, all obtained earlier, and snowfall intensity P into Equation (4), snow concentration at height Z can be obtained. Substituting the snow concentration thus obtained and the related wind velocity at height Z into Equation (1) yields mass flux of snow. Substituting that value into Equation (2) yields visibility.

The above manipulations clarified methods to estimate visibility using wind velocity, snowfall intensity and temperature. However, blowing snow is not generated below a certain wind velocity or above a certain temperature. Therefore, using the results of Takeuchi et al. (1986) on the threshold wind velocity for blowing snow (Figure 3), calculations were made for two cases:

- blowing snow accompanied by suspension snow (temperature < -2 ℃ and wind velocity ≧ 8.5 m/s), and
- negligible suspension snow (temperature ≧ -2 ℃ or wind velocity < 8.5 m/s).

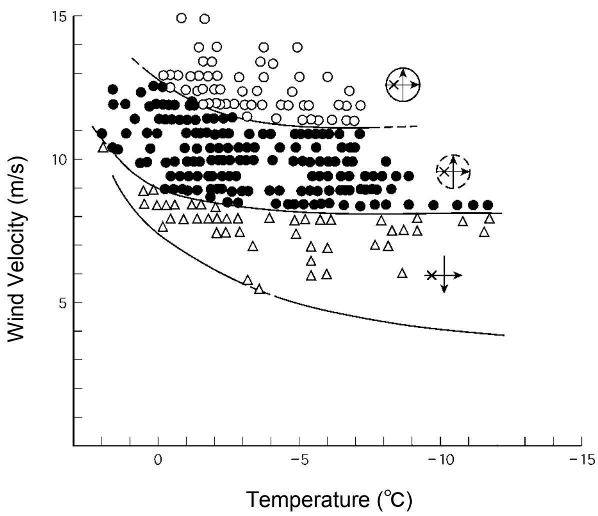

Figure 3: Threshold wind velocity and temperature for drifting snow (Takeuchi et al., 1986) (○: Continuous drifting snow high above the ground, ●: Intermittent drifting snow high above the ground, △: drifting snow close to the ground)

Although Figure 3 is based on the wind velocity measured at a height of 7 m, the difference in wind velocity between 7 m and 10 m was negligible. Therefore, wind velocity at a height of 10 m was used for the calculations described later, except where otherwise stated.

3. Calculations

3. 1 Blowing snow accompanied by suspension snow

Calculations were made for five snowfall intensities: 0 mm/h, 0.5mm/h, 1 mm/h, 2mm/h and

5 mm/h. Five wind velocities were used: 8.5 m/s, 12.5m/s, 17 m/s, 21m/s and 25 m/s.

In an attempt to verify the validity of the calculation methods, they were compared with visibility and weather data gathered at CERI's Ishikari Blowing Snow Test Field. The data used are the average wind velocities and visibilities per minute at 1.6 m above the snow-covered field surface, recorded using visibility telemetry between 03:00 and 04:00 on December 22, 2000. The depth of snow cover at the field was 38 cm at 15:00 on December 21 and 43 cm at 09:00 on December 22, indicating that light snow must fell intermittently during that time period.

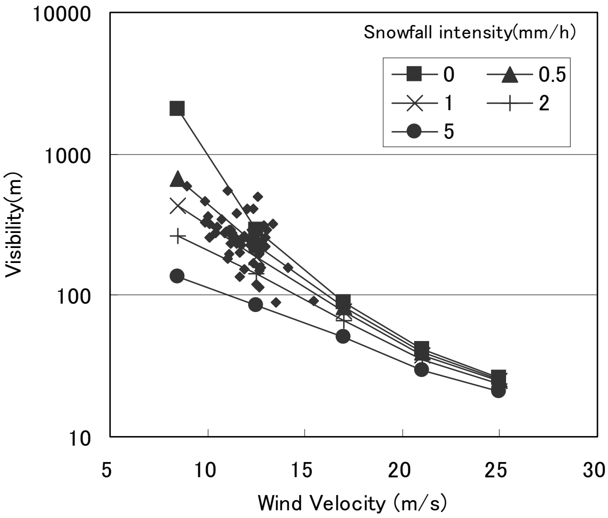

Figure 4: Comparison of calculated and measured values for a height of 1.6 m above the snow-covered field surface (◆: measured from 03:00 - 04:00 on December 22, 2000, ■: calculations for snowfall intensity = 0 mm/h, ▲: calculations for snowfall intensity = 0.5 mm/h, ×: calculations for snowfall intensity = 1 mm/h, ＋: calculations for snowfall intensity = 2 mm/h, ●: calculations for snowfall intensity = 5 mm/h)

Figure 4 shows the distribution of wind velocity and visibility measured during this time period, and the visibility calculated for a height of 1.6 m with the snowfall intensities of 0, 0.5, 1, 2, 5 mm/h. The calculated visibility is shown to closely represent the observed phenomena from 0 to 1 mm/h of snowfall intensity. It indicates that the calculation methods are generally applicable.

3. 2 Blowing snow with negligible suspension snow

Calculations were made for three snowfall intensities: 0.1 mm/h, 1 mm/h, and 5 mm/h. Five wind velocities were used: 0 m/s, 2 m/s, 4 m/s, 6 m/s, and 8.4 m/s.

As there might be cases in which the influence of the falling velocity of snowfall particles on each wind velocity was not negligible in weak wind condition, the following equation was used in place of Equation (1) to calculate mass flux of snow Mf.

$$Mf = N\sqrt{V^2 + w_f^{\,2}} \qquad (7)$$

Figure 5 shows the results of the calculations. When there was only snowfall, visibility never dropped to 100 m or below even during the extremely intense snowfall of 5 mm/h. However, visibility dropped below 200 m at a wind velocity of 8 m/s, which indicates that visibility can be lowered substantially by snowfall particles alone.

In an attempt to verify the validity of the calculation methods, the results of calculation were compared with the visibility data obtained under monsoon by Saito (1971). Saito (1971) derived the following equation from the measurement data. It represents the relationship between visibility Vis(m) and snowfall intensity P(mm/h).

$$Vis = 1150 \cdot \left(\frac{5}{3} P \right)^{-0.76} \quad (8)$$

Figure 6 is the same as Figure 5, except that the wind velocity has been replaced by snowfall intensity and the calculations obtained using Saito's equation have been added. It is shown that the visibility obtained by our methods agrees roughly with Saito's measurements for a wind velocity of just below 5 m/s. Saito (1971) did not mention the specific wind velocity at the time of h is visibility observation. However, as he wrote that the snowfall at that time was under monsoon conditions, the wind velocity of 5 m/s appears reasonable.

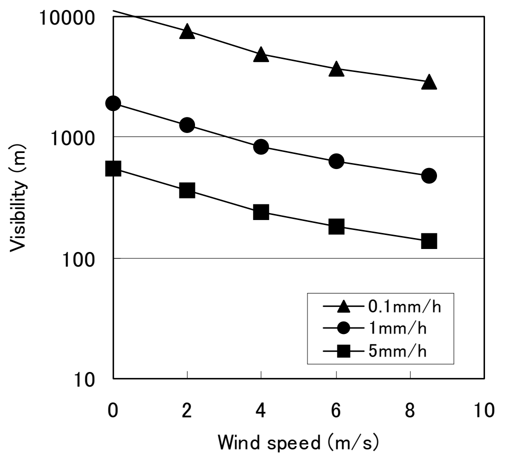

Figure 5: Calculated visibility for a height of 1.2 m with no drifting snow particles (▲: snowfall intensity = 0.1 mm/h, ●: snowfall intensity = 1 mm/h, ■: snowfall intensity = 5 mm/h; The three wind velocities of 1 m/s, 5 m/s, and 8 m/s were used for each snowfall intensity.)

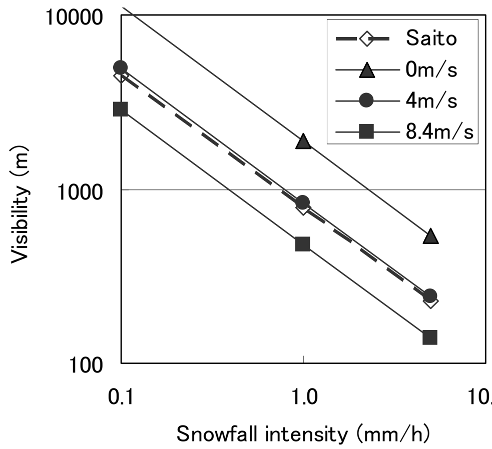

Figure 6: Relationship between snowfall intensity and visibility when wind velocity is less than 8.5m/s
□ : calculations using Saito's (1971) equation derived from his measurements,
▲: calculations using the equation derived from our study (wind velocity = 1 m/s),
●: calculations using the equation derived from our study (wind velocity = 5 m/s),
■: calculations using the equation derived from our study (wind velocity = 8 m/s)

4. Conclusion

We studied methods for estimating visibility using meteorological data that are available relatively easily, in order to understand the region-wide status of blowing-snow-induced poor visibility, a problem associated with winter road maintenance.

Methods were derived for estimating visibility under the meteorological conditions of intermittent drifting snow high above the ground, a wind velocity of 8.5 m/s or more, and temperature of less than -2 ℃. Calculations using these methods were found to accurately represent actual blowing snow phenomena. It was found that the methods apply also to cases in which drifting snow particles can be ignored.

Given this, it appears that the visibility estimation methods derived in the study can be used to understand the region-wide status of blowing-snow-induced poor visibility. However, localized blowing snow on roads can be affected by localized conditions, such as those of topography and the availability of snow protection facilities. This calls for further study.

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