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SNOWDRIFT EXTENT ON MOTORWAYS WITH BUSY TRAFFIC

ZASIĘG POKRYWY ŚNIEŻNEJ NA AUTOSTRADACH O DUŻYM NATĘŻENIU RUCHU

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Abstract
The paper examines the problem of snow-drafts on roads and ways of mitigating them. The results of theoretical analyses of development of snow-drafts and experimental investigations with road models are presented. Authors examined low and high blowing snows with different wind velocities, roads with road bed at terrain elevation and situated on an embankment, with and without snow protective facilities and with variable amount of traffic. Based on the conducted analyses a set of recommendations for snow protection of roads are provided.

Keywords: snow-drift, snow-fall, wind velocity, snow-protection, snow removal, roadway, car, traffic, model, experiment

Streszczenie
W artykule dokonano analizy problemu występowania zaśnieżania dróg oraz opisano sposoby ich ochrony przed tym zjawiskiem. Przedstawiono także wyniki analizy teoretycznej przyczyn zaśnieżania dróg oraz wyniki badań eksperymentalnych z wykorzystaniem modeli dróg. Badano wpływ małych i dużych opadów śniegu występujących przy różnej prędkości wiatru na drogę usytuowaną w poziomie terenu (zero niwelety) i na nasypie, z uwzględnieniem wpływu obecności zasłon przeciwśnieżnych oraz niewielkiego ruchu pojazdów Na podstawie wykonanych analiz sformułowano zalecenia dotyczące ochrony drogi przed opadami śniegu.

Słowa kluczowe: zaspy śnieżne, opady śniegu, prędkość wiatru, ochrona przed śniegiem, odśnieżanie, jezdnia, samochód, ruch drogowy, model, eksperyment

1. INTRODUCTION

Russia is a northern country with long winters, low below-zero temperatures, harsh winds, snow falls and snowstorms. Hence, it has a vast experience successfully preventing and removing snow drifts from auto roads. In recent years, however, it has become clear that all this is no longer enough: the main auto roads equipped with powerful snow removing systems and protection means against snow drifts witness prolonged many kilometers long traffic jams caused by snow drifts on the traffic bearing part of auto roads. This means that old, tried-and-true methods and ways do not suffice any more. Why is it?

2. THEORETICAL ANALYSIS

Presence of cars on the traffic-bearing surface of the road affects snow relocation over the road drastically. Most diagrams describing wind-blown snow stream coming across road bed of the motorways and snow-retaining barriers along the roads work for the cases when there is no traffic on the road [5-10]. Hardly any diagram features a car. Safety barriers are also predominantly absent. That was true at times when traffic was small. Nowadays, however, the conditions have changed drastically – even local roads in winter have relatively busy car traffic. Taking into account fast-paced motorization of the society we can expect further increase in traffic. This feature – lack or presence of a car, several raws of cars on the traffic-bearing surface of the road – changes the aerodynamic system on the road bed drastically and therefore changes blowing snow accumulation. A car on the road, safety barriers on the road shoulders (mandatory for embankments 2 and more m high), on motorways in the centre of the road bed – all of them obstruct wind-blown snow stream with the expected results.

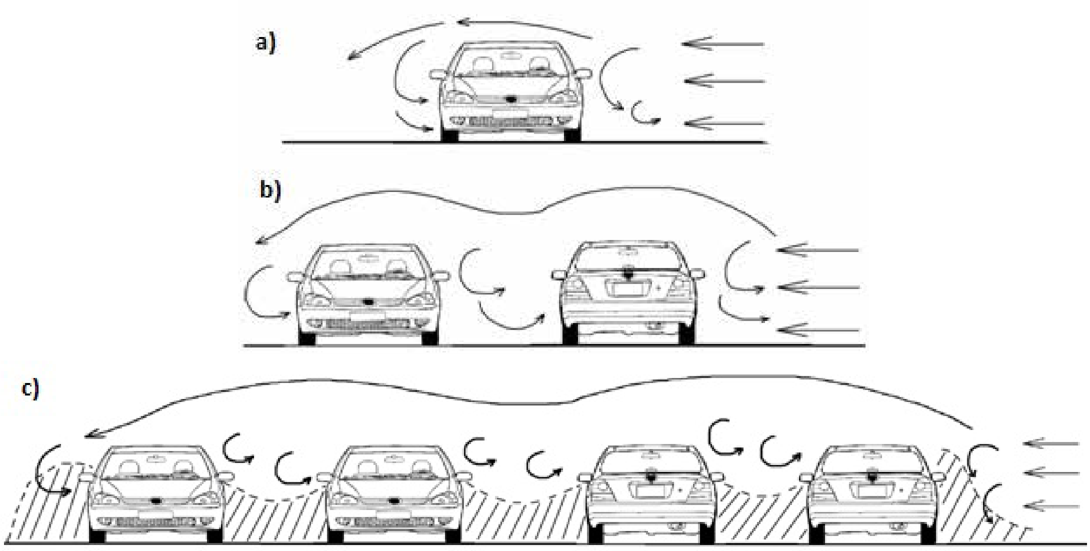

Fig. 1. A diagram of snow and wind flow movement over the road traffic bearing surface with cars moving on it. Cross profile: a) one row of cars on the traffic-bearing surface, b) two rows of cars on a two-lane road, c) cars moving in four rows

These obstacles are located directly on the road bed (barriers 0.5 m away from the embankment edge) and on the traffic-bearing surface (cars). As a result the whole point of the embankment construction (from the snow protection point of view) disappears. This is why it is not feasible to build embankments more than 2 m high. Lower embankments (up to 1.5 m high) and shallow slopes (from 1:3 to 1:8-1:10) providing gentle shapes to the road bed are fairly rare. Barriers 0.5-0.6 m high serve as standard snow-retaining fences. Cable barriers retain very little windblown snow.

Traffic flow on the road in its essence is a close barrier with gaps that are formed not within the sheets, but between the cars, i.e. along the length of the road (between the continuous sheets). On roads with multiple lanes there are as many rows of barriers as there are car lanes. These barriers are also locates very small distance 1-2 m apart. Car movement does not play any significant role.

As a result we get a brand new picture of wind-blown snow flow over the traffic-bearing surface of the road (Fig. 1).

3. MODELLING OF THE WAY WIND-BLOWN SNOW COMES ACROSS OBSTACLES

Dynamic processes modelling is based on the provisions of the dimensional analysis. Ensure similarity of the model and actual conditions to examine hydraulic and aerodynamic phenomena. The phenomena are considered to be similar if they take place within geometrically similar systems, featuring processes of the same physical nature and the relation between the same-name values is maintained. Newton's condition (Ne) shall be observed to ensure hydraulic similarity of the systems hydraulics- and aerodynamics-wise:

$$F_a\, l_a/M_a\, V_a^2 = F_m\, l_m/M_m\, V_m^2 \qquad (1)$$

where: F – energy, l – geometrical dimensions, M – mass, V – speed, a – actual parameters, m – model parameters.

This condition may be satisfied if the following four criteria are met:

- For systems under gravity – Froude number (Fr): $V_a^2/g\, l_a = V_m^2/g\, l_m$, g – gravitation acceleration. For these systems the relation between speed and length scale is expressed by the functional connection $\alpha_v^2 = \alpha_l$, where α_v – scale of velocity, α_l – scale of length.
- For systems under the internal friction force – Reynolds number (Re): $l_a V_a/\nu_a = l_m V_m/\nu_m$, ν – viscosity. For these systems the relation between speed and length is expressed by the functional connection $\alpha_v\, \alpha_l = \alpha_\nu$, α_ν – scale of viscosity.
- To ensure homochronicity of the systems make sure that Strouhal number is observed (Sh or H_0): $l_a/V_a\, t_a = l_m/V_m\, t_m$, t – time.
- Euler number (Eu): for pressures $\Delta p_a/\rho_a\, V_a^2 = \Delta p_m/\rho_m\, V_m^2$, Δp – drop in pressures, ρ – density. For potentially bulk forces $g\Delta Z_a/V_a^2 = g\Delta Z_m/V_m^2$, ΔZ – drop in pressures.

Strouhal number applies to transient processes. For steady-state processes homochronicity is not relevant and is excluded from the similarity conditions.

For negligibly small viscosities Euler number shall remain constant and shall not depend on the Reynolds number. This lack of dependency means that similarity in this case is established automatically provided similarity condition and geometrical similarity of the systems are observed. The main indication that the systems are similar is the equality of the resistance factors of the model and actual flows.

Years-long practice of modelling hydraulic and aerodynamic processes shows that all similarity criteria cannot be achieved simultaneously. This is why we will examine the listed criteria in relation to the examined scenario and will chose the most determinant one.

In this case we are examining a set air flow regime (hence, Strouhal number is excluded from the similarity conditions). Wind-blown snow viscosity is negligibly small, which means that Euler number does not depend on Reynolds number. So Euler number may also be excluded from the similarity condition.

Reynolds number reflects the effect of inner friction forces (i.e. viscosity of the moving medium) on the dynamic process. For wind-blown snow stream air flow friction against ground surface free from any obstacles shall be evaluated in different ways: for ground blizzards (low drifting snow) it is quite high as it tears snow particles away from the snow cover and relocates them (movement by saltation); for upper drifting snow it is low, as the snow mainly enters air flow through snowfall. In case there are obstacles (bushes, trees, fences, etc.) the friction increases sharply which affects dynamics and travel time characteristics of the air (wind-blown snow stream) flow. Cars on the traffic bearing surface of the road also serve as considerable obstacles generating the flow. This is why Reynolds number shall be taken into consideration during modelling of blizzards on the roads.

Froude number which reflects gravity effects and therefore snow sedimentation and snowbanks formation shall also be taken into account during modelling of snowdrifts.

Hence, the analysis has showed that there are two primary similarity criteria: Reynolds number (reflecting travel time characteristics of the flow) and Froude number (reflecting the turbulence of the flow and flow particles settling). However the correlation of modelling scales for these criteria and geometrical scale (mandatory for each case) is different:

– as per Froude $\alpha_v = \sqrt{\alpha_l}$,
– as per Reynolds $\alpha_v \, \alpha_l = \alpha_v$.

Same similarity criteria are also used in aerodynamics: Froude number, Reynolds number $Fr = V^2_\infty / L\,g$,

$$Re = L\,V_\infty / \nu \qquad (2)$$

For example, for airborne vehicles actual drag "X" and model drag are connected through an equation $X_a = X_m\, c_a\, q_a\, S_a / c_m\, q_m\, S_m$, where: c – drag factor; q – velocity head pressure ($V^2/2g$); S – reference area. Main parameters of the oncoming flow are: speed (V_∞), pressure (p_∞), density (ρ_∞), temperature (T_∞), dynamic viscosity coefficient (μ_∞) or kinematic viscosity coefficient (ν_∞).

For aerodynamic processes like an air vehicle air flow Froude number is fairly insignificant as the effect of gas weight on the motion is negligibly small. However, for wind-blown snow stream with a large number of snow particles this criterion is as important as it is in hydrodynamics.

Main purpose of the Reynolds number is to predict flow pattern of a laminar or turbulent flow. For eddy flow turbulence degree is assessed (based on Re). Reynolds number evaluation requires availability of the kinematic viscosity coefficient. Its values in water and air are significantly different (Fig. 2).

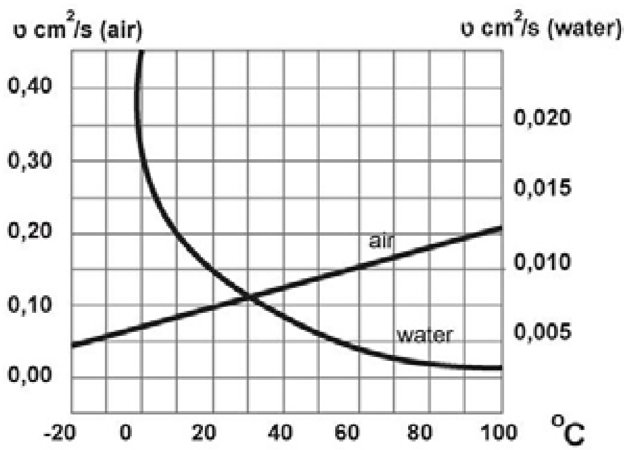

Fig. 2. Kinematic viscosity coefficient of water and air Dotted line – author's forecast for the below-zero temperatures

Viscosity – value reflecting friction forces in liquids and gases. For jet liquids and gases N.P. Petrov proposes to use the following correlation

$$T = +/- \mu F\, dU/dn \qquad (3)$$

where: T – full friction; F – surface area of the bodies in rubbing contact; dU – drop in the speed of the stream during the transition from one layer to another; μ – dynamic viscosity factor: $|\mu| = |(T/F)\, dU/dn)|$.

Kinematic viscosity coefficient ν:

$$\nu = \beta\, V 1, \quad m^2/s \ (cm^2/s) \qquad (4)$$

where: β = 0.31…0.49 – coefficient depending on the velocities distribution law and the way gas molecules collide during their thermal movement; l – length of the free path of gas particles between two collisions; μ – dynamic viscosity coefficient.

Length of the molecules' free path $l = 1/(\sqrt{2}\ n_o\ \delta)$, where: n_o – number of molecules in a volume unit; δ – molecule effective cross section: $\delta = \pi d^2$, d – effective diameter of the molecule (for Oxygen O_2 – d x10^{10} = 2.9…3.6 m); d decreases as the temperature increases: $d_t = d\ (1 + C/T)^{-2}$; T – temperature in K; C – gas constant: for Oxygen C = 138 K.

After an examination of the equation in terms of Froude and Reynolds numbers we get an equation to assess the speed of movement:

– asper Froude

$$V_{mod} = V_{act} \sqrt{L_{mod}} / L_{act} \tag{5}$$

– asper Reynolds

$$V_{mod} = V_{act}\ L_{act}/L_{mod} \tag{6}$$

Hence, «as per Reynolds» modelled speed shall be higher than the actual speed (which falls in line with the equivalent results in aerodynamics).

Snow particles (snowflakes) in the air flow may be treated as suspended load in a water flow. Suspension is a result of flow turbulence.

In upper and overall drifting snow creating largest snow depositions (snowbanks) air flow carries a lot of snowflakes. They join the air flow as a result of snowfall (snow falling from the clouds) and partially as a result of snowflakes being torn away from the snow cover on the ground and lifted by a turbulent flow to the height of several meters. These particles are transported by wind. Snow relocation intensity I is defined by the wind speed V:

$$I = C\ V^3 \tag{7}$$

Decrease in speed causes a drop in the wind ability to transpont and maintain snow content in the air flow. Increased turbulence areas before and after wind-blown snow stream obstacles make the flow speed drop drastically, causing snow sedimentation (falling).

For liquid flows transporting snow drifts (i.e. for double-phase liquids) M.A. Velikanov proposed to introduce fluidization action into the stream force equation, reflecting it through an average speed of particles falling w. This speed is considered equal to the hydraulic size of the snow drifts' particles (w_0).

It has been established that for the fluidization processes in geometrically similar systems to be similar the following equation shall be observed

$$\alpha_v = \alpha_{wo}\ \alpha_s \tag{8}$$

where: s – mean value of the suspended materials concentration in the examined volume; α_{wo} α_s – modelling scale.

Particles sedimentation speed W depends on their size and relative weight. The following three criteria shall be observed during modelling of snow drifts:

1. $Re = V\ d/\nu > Re_m$.
2. V/w_o = idem.
3. $V^2/(g\ \rho\ d)$ = idem,

where: Re_m – threshold Reynolds number value; V – speed; d – diameter (size) of particles, ν – kinematic viscosity coefficient; w_o – hydraulic size of particles; ρ – density of particles. The size of snow particles (snowflakes) falls within 0.1 to 5, sometimes 10 mm (and different shapes). Snow density in freshly fallen deposit can be as high as 0.07…0.12 g/m³.

If the actual $Re_a > Re_m$, then the flow past an obstacle regime will be squared and Re_m shall also be higher than Re_m. If $Re_a < Re_m$, similarity may be achieved only in case $Re_a = Re_m$.

Criterion $V^2/(g\ \rho\ d)$ belongs to the conditions of bottom drag of solid particles and requires equal scales of $\alpha_{wo} = \alpha_v = \sqrt{\alpha_h}$, which is a result of kinematic similarity.

Suspended sediment concentration of a flow S depends on the geometric dimensions of the particles (d), values of V and w_o. As the diameter of particles becomes more disperse (D/d_{cp}) suspended sediment concentration of the flow is achieved at higher values of V/w_o.

$$S = 0.009\ (V_{lim}/w_o)^6\ (d_{cp}/D)^{3.5} \tag{9}$$

where: V_{lim} – speed required to relocate a given number of suspended solid particles of a certain granulometric texture.

4. EXPERIMENTAL STUDY

We have examined a 1:60 scale road bed model of a motorway constructed at zero elevation and on an embankment (model – 3 cm, actual size – 1.8 m) operating during ground blizzard at wind speeds from 5.0 m/s to 1.3 m/s (actual speed 38.7-10.1 km/h) with and without a snow-retaining barrier at the windward side of the road (fence). Traffic bearing part of the road has two lanes where: there are no cars; there is one row of cars (i.e. cars use one lane); there are two rows of cars (i.e. cars use two lanes). Snow imitation has been added to the air flow.

For modelling results see diagrams showing how the speed of the air flow changed as it came across the motorway.

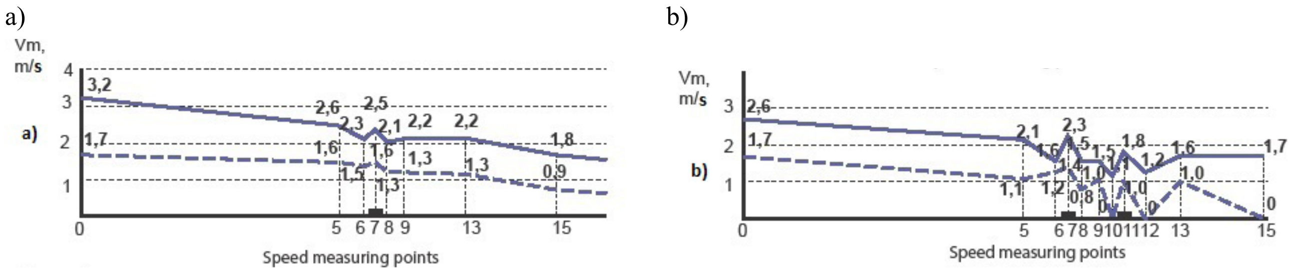

Fig. 3. Ground blizzard. Road bed at 'elevation zero'. No snow-retaining barrier. Cars form 1 (Fig. 3a) and 2 (Fig. 3b) rows. There are 2 curves on the diagram showing velocity profile of the air flow for different initial air flow speeds

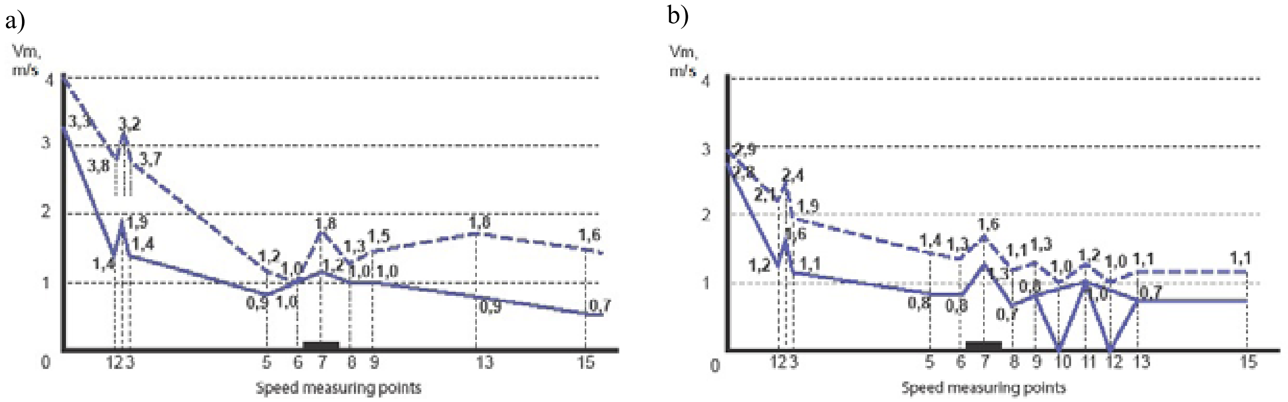

Fig. 4. Ground blizzard. Road bed at 'elevation zero'. There is a snow-retaining barrier in front of the road. Cars on the road form 1 (Fig. 4a) and 2 (Fig. 4b) rows

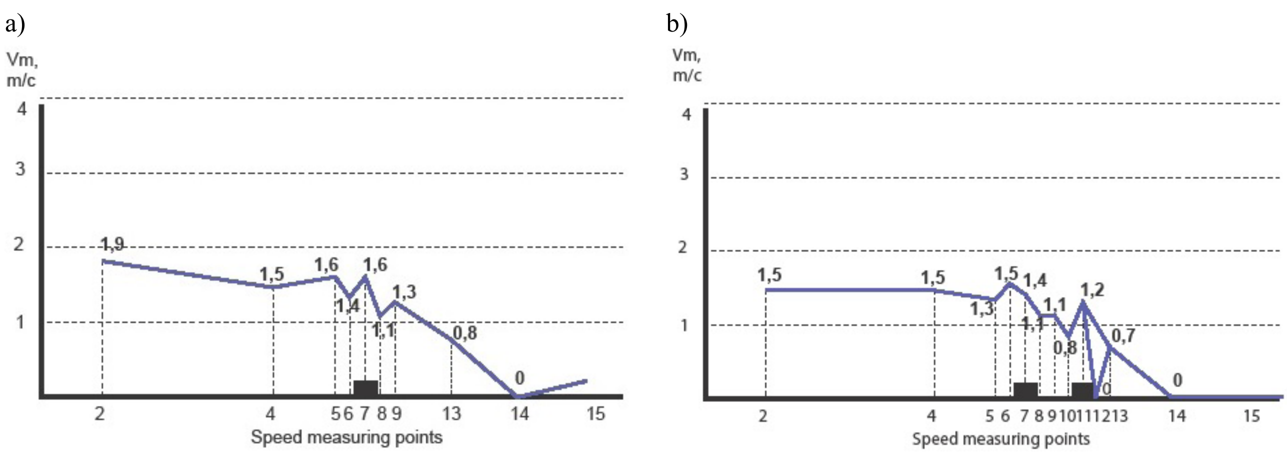

Fig. 5. Ground blizzard. Road bed on an embankment. No snow-retaining barrier. Cars form 1 (Fig. 5a) and 2 (Fig. 5b) rows

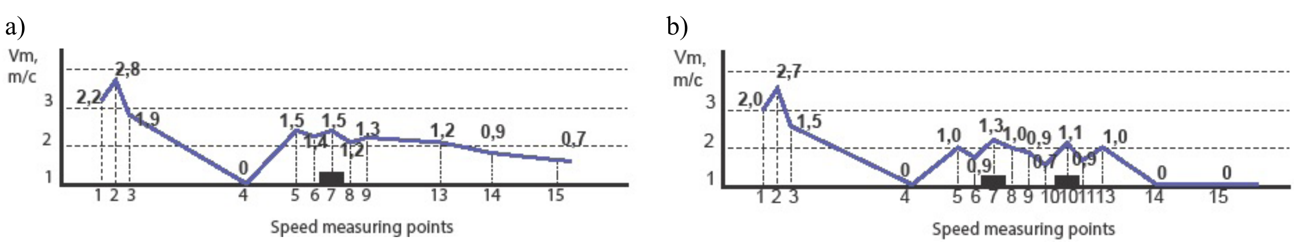

Fig. 6. Ground blizzard. Road bed on an embankment. There is a snow-retaining barrier in front of the road. Cars form 1 (Fig. 6a) and 2 (Fig. 6b) rows

For visual representation of snow drifts sedimentation refer to Figures 7-9.

Fig. 7. Top view of the snow drift build-up close to cars on the traffic-bearing surface of the road. Road bed at 'elevation zero', no snow-retaining barrier

Fig. 8. Sedimentation of snow drifts on the traffic-bearing surface of the road (embanked section) during ground blizzard. No snow-retaining barrier

Fig. 9. Sedimentation of snow drifts on the traffic-bearing surface of the road built on an embankment with a snow-retaining barrier. Ground blizzard

5. RESULTS

Changes in the air speed over traffic-bearing surface of the road showed that in ground blizzard (air flow height up to 2…3 m) car flow on the surface of the road contributes to blizzard drifts and therefore – formation of snow drifts. Regardless whether there is a snow-retaining barrier in front of the road or not. The number of car rows is important. Two occupied lanes creates several sharp speed drop areas: before and after the first lane, before and after the second one. The rate at which the wind speed decreases grows (sometimes down to 0 m/s). The lower the wind speed during snow drift, the more prominent this drop becomes. At high wind speeds solid particles are blown away from the traffic-bearing surfaces through the space between the cars in the lane and while the amount of snow is larger, on the whole the amount of solid drifts is less than with blizzards with relatively low wind speed. The study goes on. However already it is safe to say that snow barriers placed to the windward side of roads with busy traffic shall be retained to catch the snow carried by low drifts and ground blizzards; they shall be reinforced with blow-over snow fences (with or without a clearance in the bottom part) on the edge of the road bed – like noise-abatement walls – to ensure protection against snow carried by the high-up drifting snow.

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