MODELS FOR SHORT-TERM ROAD ICE FORMATION FORECAST

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ABSTRACT

The method of mathematical simulation is used to study the conditions of ice formation on road surfaces. This model is based on the logical modules describing the conditions for road ice formation. Simple principles for icing forecast were obtained. Practical application the results of these researches is described.

1. Introduction

Upgrading of road safety during the winter period at the sacrifice of keeping pavement from ice formation is one of the topical problems of ground traffic. Usually slipping on roadway coverings is eliminated by the use of anti-icer and deicer salts. However, the more efficient way is to allow no formation of an ice layer and, hence, to keep high rideability and road grip of a tyre. The solution of the above problem is possible with the availability of a specialized road ice prediction.

The process of ice formation is very intricate, it is influenced by many weather and road factors and the degree of dependency from these parameters we can't be explained. The problem of road ice prediction is complicated. It cannot be solved by using the conventional research methods. To solve this problem it is necessary to use the method of mathematical modelling and computing experiment.

The mathematical model based upon the calculating analysis of the pavement temperature and the logical modules describing the conditions for ice formation on a road has been developed for the investigation of the process. The model allows one to complete the calculating experiment with the use of a personal computer IBM with the followed data handling. The physicostatistical dependencies for the prediction allowing one to predict the ice formation 3 - 6 hours prior to its onset have been obtained. The model inables to investigate the dynamic behaviour of the "road-environment" system during the formation of slipping of various types

2. Mathematical modelling of road ice formation

"Road-environment" system is a complex heat-and-moisture exchange model. The law of its functioning may be represented by the operator Fs. This operator transform the set of inside independent systems parameters into outside dependent variables (Sovetov and Jakovlev, 1985).

$$\overline{y(t)} = F_s[\overline{v(t)}, \overline{h(t)}, t] \qquad (1)$$

where $y(t) = \{y_1(t), y_2(t),..., y_n(t)\}$ the vector of output dependent variables, F_s the law of systems functioning, $\overline{v(t)} = \{v_1(t), v_2(t),..., v_m(t)\}$ the vector of the ambient conditions effect, $\overline{h(t)} = \{h_1(t), h_2(t),..., h_k(t)\}$ the vector of the proper systems parameters, t - the time.

Equation (1) is a dynamic mathematical model of the system in winter period. Operator F_s may be presented as logical relations describing the conditions of ice formation on road surface.

In winter roads can become slippery in a number of ways. There are seven states of road surface.

1. *Dry surface.*
2. *Wet surface.*
3. *Ice-crusted.* This kind of road slippery is formed when water on the surface freezes to a thin coating of ice. It is possible when the surface temperature drops below $0\,^0$C.
4. *Hoar frost.* The conditions of its formation are: clear weather, negative radiation balance (radiation loss), high humidity, surface temperature lower than $0\,^0$C and at the same time, lower then the dew point.
5. *Freezing rain.* It is formed when rain whose temperature is a little above $0\,^0$C falls onto a cold surface. On contact with the cold surface the rain drops are cooled and crystallized to ice.
6. *Glaze.* This kind of the road slippery is formed when rain is supercooling , that is the temperature of the rain drops is lower then $0\,^0$C and when they fall onto a surface whose temperature is about $0\,^0$C or lower, they freeze instantaneously to ice.
7. *Hard snow.* This kind of the road slippery takes place when snow on a highway surface becomes compacted by the action of traffic.

The inside parameters were separated into two groups: meteorological conditions $v(t)$ and road factors $h(t)$.

The surface temperature is a main factor defining ice formation on road pavements. It is formed under the influence of all road parameters. However, the degree of their influence is different and unknown. The surface temperature can be received by calculation with the mathematical model. In order to calculate the surface temperature heat conductivity equation with II and III kind boundary conditions was solved.

Road construction and soil half-space is a multilayer system. Each layer has the following heat –physical properties: thermal conduction λ and specific heat c. This parameters are the functions of coordinate x, time t, temperature T, road materials density ρ and moisture content (W_r).

The following problem has been solved to define the temperature fields in road construction and the surface temperature:

$$c\rho\frac{\partial T(x,t)}{\partial t} = \frac{\partial}{\partial x}[\lambda\frac{\partial T(x,t)}{\partial x}] \qquad (2)$$

where $T(x,t)$ is the temperature at depth x in road construction at t.

There is a complex heat exchange with surrounding air on the road surface. It is defined as the boundary conditions of II and III kinds:

$$\lambda\frac{\partial T}{\partial x} + \alpha[T_s(t) - T_{ae}(t)] = 0 \qquad (3)$$

where T_{ac} is the "conditional" air temperature

$$T_{ac}(t) = T_a(t) + \frac{\rho_s q_s}{\alpha_c} \qquad (4)$$

ρ_s - the incident radiation absorption coefficient, q_s - is the intensity of heat flow, α - is the heat-exchange coefficient.

Intensity of heat flow depends on the energy balance at the road surface and all its components may be determined by the actinometric methods (Kondratjev K.J., 1965). Formula for calculation contains such parameters as cloud cover, celestial altitude, geographical latitude, longitudinal profile, road bearing, vapour pressure, road surface colour and roughness of road surface.

To calculate convectional heat exchange coefficient α_c the empirical formula was used (Ivanov, 1973)

$$\alpha_c = \frac{0.00058V^{1.15}h_r^{0.15}\lambda_a}{\gamma_a^{1.15}} \qquad (5)$$

where λ_a is the air thermal conductivity, γ_a is the air kinematic viscosity.

The second boundary condition is a constant temperature on the depths of temperature oscillation damping H:

$$T(H,t)=T_c=const \qquad (6)$$

The initial temperature distribution was calculated by the formula (Zolotar, *at.al.*, 1971):

$$T(x,0) = T_{a.av} + (T_s - T_{a.av})\frac{R_s + \sum R_x}{R} \qquad (7)$$

where $T_{a.av}$ is the monthly average air temperature, R_s the thermal resistance of road surface, $\sum R_x$ that of road layers higher then x depth, R is the total thermal resistance of all road layers and road bed until H depth.

To solve the formulated problem the method of finite differences was used (Beljaev and Rjadno, 1982). Mesh width on time is uniform and makes up 15 minutes, and that on coordinate x is irregular, it is the least in upper layer of the road construction (0,01 m) and the biggest in the road bed (0,1 m). This mesh width size provides convergence of numerical solution to approximate value by virtue of its second order approximation, as well as its unconditional stability.

To simulate the conditions of ice formation on a road surface the meteorological reports of Voronezh weather station over the 20-years period where used. The meteorological parameters are measured every 3 hours. To obtain intermediate information in the nodes of a mesh linear interpolation was applied.

The program complex SIGNAL for IBM computer was developed. Algorithm is realised on FORTRAN.

At the first stage of the computing experiment the statistical information of icing risk potential cases over the 20-year period is formed.

3. Models for short-term road ice formation forecast

Linear discriminant functions where calculated to forecast road ice formation. They are used in meteorology to predict the dangerous weather phenomenon. To obtain this models the results of the first stage of computing experiment are used. There are two sets of information. The first named "ice presence" $\{X_1\}$ includes meteorological parameters and road surface temperature in the beginning of the ice formation. The second set $\{X_2\}$, named "ice absence" includes the same parameters the day before. The form of the discriminant function is:

$$D(x) = a_1x_1+a_2x_2+...a_mx_m+a_{m-1} \qquad (8)$$

where coefficients a_i are calculated from the condition of maximum difference of these sets:

$$\Phi = (\frac{\overline{X}_1 - \overline{X}_2}{S_x})^2 \rightarrow \max \qquad (9)$$

where X_i is the vector of average values, S_x is the mean square deviation.

To raise forecast reliability "screening" procedure was used. For the selection of the significant parameters the Machalanobis distance Δ^2 was employed (Bogatkin and Enikeeva, 1985)

$$\Delta^2 = (\overline{X}_1 - \overline{X}_2)^T V_m^{-1}(\overline{X}_1 - \overline{X}_2) \qquad (10)$$

where V_m^{-1} is the inverse covariance matrix.

Thus, the most significant parameters are included into forecast models. Standard computer programs of discriminant analysis were used.

To verify the sufficiency of the models for simulation of the road surface temperature the field observations where carried out. During these experiments the road surface temperature was measured. These researches took place during two winter seasons. The results of the mathematical simulation were compared with the experimental data. Arithmetical mean of the absolute error is equal to 0,52 ° C and the upper boundary of the confidence interval for 0,9 fiducial probability is equal to 0,62 ° C. Therefore the mathematical model for road surface temperature simulation has reliability sufficient for the formulated problem. To estimate the reliability of the models for simulation of road surface conditions the information about surface conditions on the roads (over the 6-years period) and on runway of civil aerodrome (for the same period) were used. 161 cases were analyzed. The mean convergence is equal to 85 % and is changed from 79,2 % for glaze to 88,4 % for hard snow. This reliability may be sufficient for practical problems.

Mathematical treatment the results of computing experiment was made to obtain the models for the short-term prediction of road icing.

$$-6{,}0 < T_a < -0{,}5 \qquad (13)$$

Arrow shows the direction of parameters variation.

Conditions of hour frost formation

Data handing of the computing experiment makes it possible to confirm, that this kind of road icing don't forms in the moderate-continental climate.

Conditions of freezing rain and glaze formation and their forecast

These types of road icing have the same conditions of formation. They were joined in one set for prediction. The following meteorological and road conditions are preceded freezing rain and glaze formation.

1. The wind direction is changed to the south, south-east or south-west direction.
2. The air temperature and relative humidity of air are raised simultaneously after the long frost. The stable increase of these parameters takes place during 24-12 hours before the icing.
3. At the same time the atmospheric pressure is reduced. The reduction of this parameter takes place during 24-12 hours before the ice formation.

If these conditions are taking place the measurements of air temperature and relative humidity are substituted in the discriminant function

$$y=0{,}094T_a + 0{,}103W - 9{,}138 \qquad (14)$$

The graphic interpretation of precipitation is presented on Fig. 2.

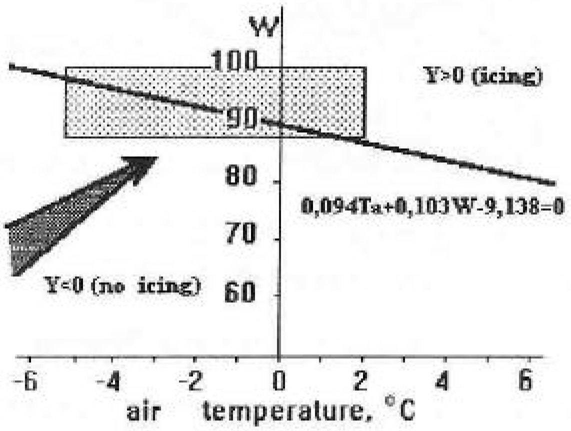

Fig. 2. Forecast of glaze formation

If the value of the function is negative the freezing rain and glaze formation is not expected. If the value of the function $y>0$ the icing is predicted. This model allows to predict the ice formation 3 hours before the process starts. The line (14) separates the parameters' values in two classes: ice formation presence (above the straight line) and ice formation absence (under the line). In order to predict the road icing the working zone is used. The boundary of this zone corresponds to upper and lower values of the confidence interval for the 0,95 fiducial probability:

Conditions of ice-crusted formation and its forecast

Data handing of the computing experiment makes it possible to investigate the dynamics of variation of the most significant parameters. The following meteorological and road conditions are preceded ice crusted formation.

1. The wind direction is changed to the west, north-west or north direction.
2. Wet surface.
3. The air temperature and relative humidity of air are reduced simultaneously. The stable reduction of these parameters takes place during 6-8 hours before the icing.
4. At the same time the atmospheric pressure is raised. The increase of this parameter takes place during 9-12 hours before the ice formation, when the rain precipitation is falling.

If these conditions are taking place the measurements of air temperature and relative humidity are substituted in the discriminant function

$$y = -0{,}168T_a - 0{,}065W + 5{,}648 \qquad (11)$$

If the value of the function is negative the ice crusted formation is not expected. If the value of the function $y>0$ the icing is predicted. This model allows to predict the ice formation 3 hours before the process starts. The graphic interpretation of precipitation is presented on Fig. 1.

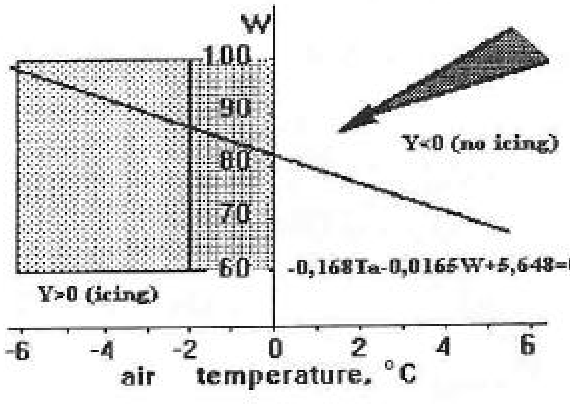

Fig. 1. Forecast of ice-crusted formation

Equation (11) is a straight line on the two dimensional subspace with coordinates (T_a, W). This line separates the parameters' values in two classes: ice formation presence (under the straight line) and ice formation absence (above the line). In order to predict the road icing the fixed zone is used. It is presented as a rectangle with a hatching and is called the working area. The boundary of this zone corresponds to upper and lower values of the confidence interval for the 0,95 fiducial probability:

$$-1{,}8 < T_a < 0{,}0 \; ; \quad 60 < W < 100 \qquad (12)$$

If the anti-icer salts were used before, the air temperature range may be expanded

$$-5{,}2 < T_a < 2{,}0 \; ; \quad 87 < W < 100 \qquad (15)$$

Arrow shows the direction of parameters variation.

. *Conditions of hard snow formation*

The main condition of its formation is a snow presence on the road surface. The snow layer may compacts when the following meteorological conditions are take place:

1. The air temperature is higher then -5° C.
2. If the air temperature changes from -5° C to -10° C the snow layer may compacts when the relative humidity of air is higher then 90 %.
3. If air temperature is higher then 0° C the hard snow is formed when the intensity of snowfall I_{sf} > 0,6 mm/h and at the same time the air temperature is reduced.

4. Concluding remarks

The models for short-term road ice formation forecast where be tested during two winter seasons (1997/98, 1998/99) in the Ice Warning System in Kolomna (Moskow region). Practical experiments with models confirmed sufficient forecasts reliability (nearly 85 %).

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