Adaptation of roads winter maintenance strategies to weather influences

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ABSTRACT

Game theory and operations research were used to study the adaptation of roads winter maintenance strategies to weather influences. Economic models in the loss-matrix form were discussed. Matrix elements take into account losses of the maintenance deports and users of roads by the various roads weather forecast alternative. All losses are divided into two components: expenditures which are necessary for the road winter maintenance and losses in the transport complex and national economy from unsatisfactory road conditions (decrease of speed on a slippery road surface, possible accident losses, the damage of polluted environment). The results of the computing tests were reported.

Keywords: winter maintenance, loss-matrix, economic benefit

1. INTRODUCTION

The analysis of the decision-making process problems for the winter maintenance make it possible conclude that snow and ice control measures are accepted by the road organization in conditions of weather situation uncertainty. This uncertainty is connected with insufficient information about weather conditions, opportunity of their change and influence on a road surface condition during the winter period.
At the winter maintenance the interests of roads maintenance service and the nature collide. They act the various purposes as two sides pursuing, hence, the conflicting situation takes place. The theory of games as the mathematical theory of conflicting situations, allows to give recommendations for the road organization as one side of the conflict.

The risk of the road organization to accept wrong strategy will depend on quality of the special weather forecasts and also from completeness and efficiency its use in the decision-making process
To investigate the weather influence on any consumer or technological process it is necessary to estimate the profit which can be received at rational use of the meteorological information.

There are two estimated parameters:

- actual economic efficiency which is calculated with the help of statistical data or inquiry,
- potential economic efficiency which is calculated on the basis of the theoretical mathematical model [6].

The model reflect reaction of the road organization or roads winter maintenance technological process on influences.

Meteorological and economic models (MEM) are used to calculate the consumer losses in negative weather conditions. They allow to estimate the results of decision-making process in various variants of the meteorological information use.

2. METEOROLOGICAL AND ECONOMIC MODELS

Main principles of MEM-construction are developed for system «Weather - Meteorology - Consumer» [6]. The general system structure for the road winter maintenance is presented on Fig.1 [5]. The choice of the road winter maintenance strategy depends on an available information (blocks 2, 4, 6), resources (the block 3) and actual surface condition of a road (the block 5).

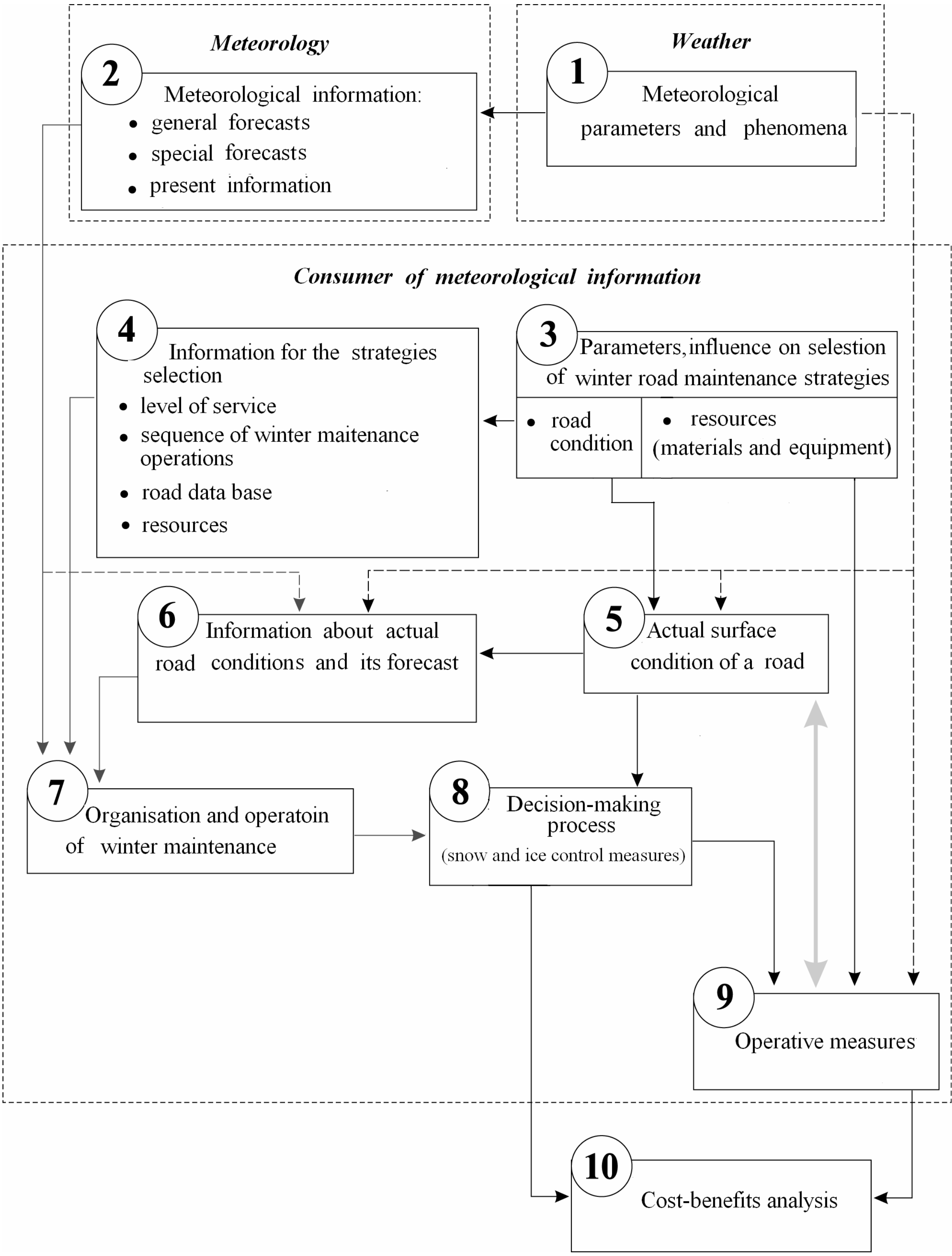

Fig. 1. «Weather - Meteorology - Consumer» system structure

For estimation the efficiency of various road winter maintenance strategy the generalize parameter is offered. It express in terms of money all losses which take place at complex weather conditions (L_{CW}). They can be divided on two components:

1) The road organizations expenditures for the winter maintenance work (E_{RO}),

2) Losses in transport complex and national economy from unsatisfactory road conditions:

- Lower speed on a slippery road surface (L_V),
- Cost of accident (L_A),

- Damage of polluted environment (L_E).

$$L_{CW} = E_{RO} + L_V + L_A + L_E, \tag{1}$$

All components in Eq.(1) depend on the weather conditions, applied road winter maintenance strategy and time slippery roads surface. They can be expressed as the calculated formulas with output parameters of road winter maintenance system [4].

The matrix of losses is presented in Table 1.

Predicted conditions F	**The decisions, accepted by the road organization**	
	Protective measures are accepted adequately, according to weather conditions	Protective measures are inadequate to weather conditions
F_1 (ice presence)	S_{11}	S_{12}
F_2 (ice absence)	S_{21}	S_{22}

Table 1. Matrix of losses

S_{11} **-** total losses which take place at complex weather conditions (road ice formation):
- for post salting technology (de-icing) $S_{11} = L_{CW}$,
- for pre-salting technology (anti-icing) $S_{11} = E_{RO}$.

S_{21} - expenses of the road organization for protective actions:
- for post salting technology (de-icing) $S_{11} = 0$,
- for pre-salting technology (anti-icing) $S_{11} = E_{RO}$.

S_{12} - losses at unexpected road ice formation. $S_{12} = E_{RO}$.

S_{22} - losses at absence of the dangerous phenomenon $S_{22} = 0$.

The matrixes of losses are calculated for one case of ice formation for the road length 1 km.

3. ROAD WINTER MAINTENANCE STRATEGIES

To calculate the loss matrix some road winter maintenance strategies have been considered. They are presented in Table 2.

Number of strategy	**The name**	**Type of road slipperiness**
I	Post salting (de-icing)	Glaze, ice, black ice
II	Pre-salting (anti-icing)	Glaze, ice, black ice
III	Mechanical clearing of snow, patrol snow removal	Fresh snow
IV	Pre-salting (anti-icing), mechanical clearing of snow	Compacted snow

Table 2. Road winter maintenance strategies

The time diagrams for all strategies have been developed [5] and presented on fig. 2-4.

Letter designation on the diagrams:

t_{bif} – the time of ice formation, t_i – the time of ice detection, t_{bw} – the time beginning of a work, t_{fw} – the time finishing of a work, t_{ct} – cycle time, t_p – the time for pre-salting work, t_c – snow accumulation time, t_{bs} – the time of snow beginning, t_{sr} – the time of snow removal, h_{ads} - allow depth of snow.

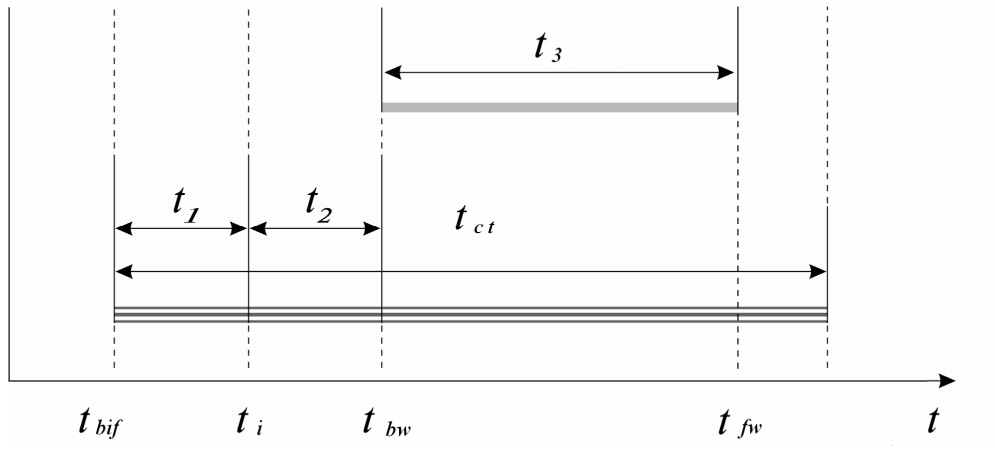

Fig. 2. The time diagram for I strategy

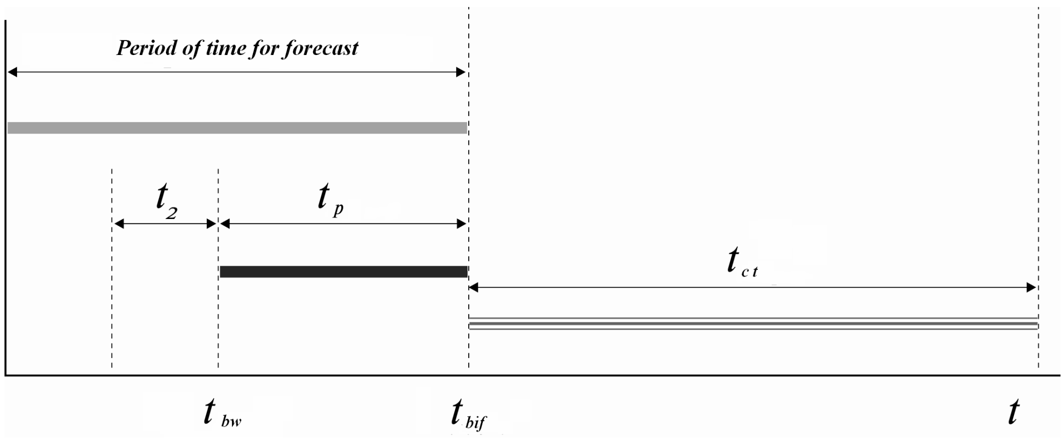

Fig. 3. The time diagram for II strategy

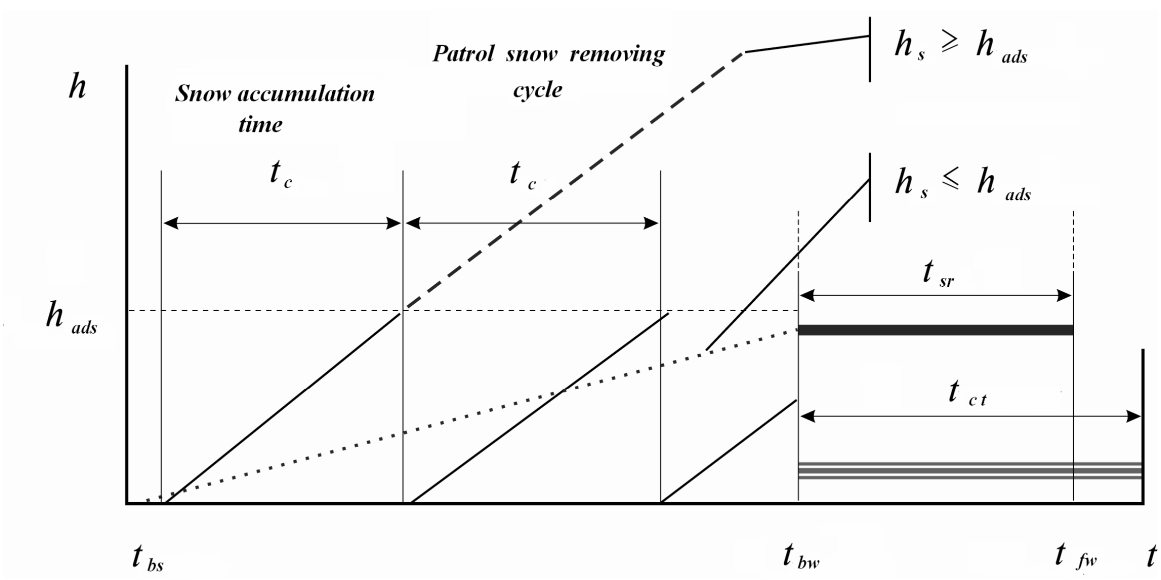

Fig. 4. The time diagram for III and IV strategies

4. CALCULATED FORMULAS FOR OUTPUT PARAMETERS

The average speed of a car free movement v_{fm} can be determined as:

$$\overline{v_{fm}} = k_{cs} \; v_d - t[a_0 + b(k_{cs} \; v_d)^2], \tag{2}$$

where k_{cs} – coefficient of calculated speed for dry, wet, icing and snowing road surface; v_d - the design speed according to normative documents, km/h; t - the width of the confidence interval; a_0, b - empirical coefficients [1].
Average speed of transport stream:

$$\bar{v} = \bar{v}_{fm} - \alpha \, \beta \, N, \tag{3}$$

where α - the coefficient considering influence of weather factors; β - the coefficient considering traffic composition; N – amount of traffic, v/h.

Accident rate is calculated under the empirical formula [1]:

$$Z = 2 \cdot 10^{-5} \, K_{tac}{}^{0.373} \, N \, t_{ct} \, L_s, \tag{4}$$

where K_{tac} – total accident coefficient for winter period; L_s – the length of the road section, km.

The estimation of ecological parameters have been received by means of damage to polluted environment:

- air contamination,
- water and soil solemnization by de-icing salts [3].

Quantity of anti- icing materials:

$$Q = 10^{-6} B L_s \sum_{i=1}^{n} q_i \, , \tag{5}$$

where q_i - norm of the anti- icing material spread, g/m^2; B –carriageway width, m.

The model of the atmospheric diffusion was used to define the air contamination. The emission intensity for all kinds of vehicles is calculated by the formula [3]:

$$q = 2{,}06 \cdot 10^{-4} m \left[\sum_{1}^{i} G_{ik} N_{ik} k_k + \sum_{1}^{j} G_{jd} N_{jd} k_d \right], \tag{6}$$

where m - the correction factor depending on average speed of transport stream; G_{ik} - average fuel consumption for carburetor cars, l/km; G_{id} - the same, for diesel cars, l/km; N_{ik}, N_{id} - intensity of movement for carburetor and diesel cars; k_k, k_d - dimensionless coefficients.

The road organizations expenditures for the winter maintenance (E_{RO}) may be calculated by cost estimating:

$$E_{RO} = C_M + C_V \tag{7}$$

where C_M – the cost of de-icing salts; C_V – operation cost of road vehicles.

Losses of lower speed on a slippery road surface:

$$L_V = \sum_{j=1}^{n} S_j N \; L_s \, t_{ct} \left(\frac{1}{V_s} - \frac{1}{V_d}\right) \tag{8}$$

where S_j – working cost of 1 v-h; V_s - speed on a slippery road surface, km/h; V_d - the same for a dry road surface, km/h.

Cost of accident

$$L_A = Z \times A \tag{9}$$

where A – accident cost.

Damage of polluted environment can be calculated under the formula:

$$L_E = \gamma \sigma f m_b A_a, \tag{10}$$

where γ - coefficient translating a ball estimation in cost; σ - coefficient for recipients structure estimation; f - the dimensionless coefficient for estimating the dispersion of impurity; m_b - total amount of blowouts; A_a - coefficient of relative aggression.

5. ADAPTATIVE PARAMETERS

For analysis the adaptation of roads winter maintenance strategies to weather influences the general matrix of losses (Tabl. 1) may be presented as the sum of two matrixes reflecting expenses of the road organizations and losses in transport complex and national economy:

$$\begin{matrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{matrix} \Bigg| = \Bigg| \begin{matrix} E_{11} & E_{12} \\ E_{21} & E_{22} \end{matrix} \Bigg| + \Bigg| \begin{matrix} L_{11} & L_{12} \\ L_{21} & L_{22} \end{matrix} \Bigg| \tag{11}$$

Protective measures at roads winter maintenance are accepted always (they can be duly and untimely), and losses in transport complex and national economy always take place: $S_{11} = E_{11} + L_{11}$ and $S_{12} = E_{12} + L_{12}$.
However, at successful and duly work and expenses and losses can be reduced $E_{12} \geq E_{11}$, $L_{12} \geq L_{11}$
Having accepted designations $E_{11}=C$, and $L_{11} = L$ we shall receive, that

$$S_{11}=C + L, \quad S_{12}=C + L_{max}=E_{11} + (E_{12}-E_{11}) +L_{12} \tag{12}$$

where $L_{max} = (E_{12}-E_{11}) +L_{12}$ - the greatest possible losses at mistrust to the forecast.

This parameter are presented at the diagram [2, 5].

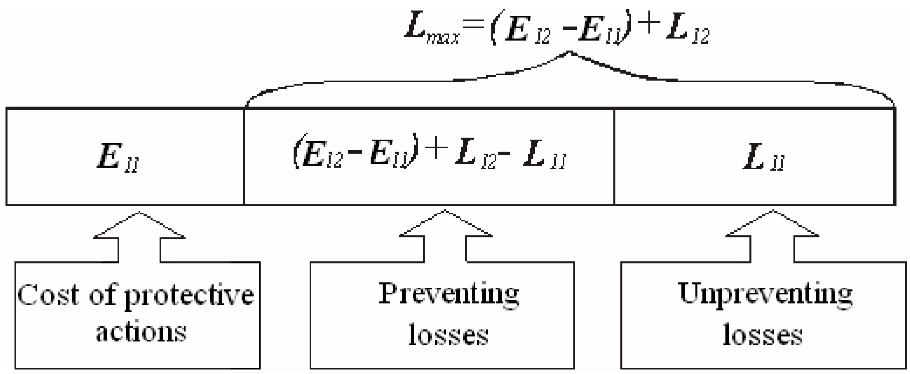

Fig. 5. The distribution diagram for possible losses at protective actions

On the basis of such diagrams is entered with some parameters, allowing to estimate adaptability of the consumer or technological process to weather influences [2].

1) Parameter of unpreventing losses:

$$\varepsilon = L_{11} / [(E_{12} - E_{11}) +L_{12}] \tag{13}$$

If expenses of the road organization are equal $E_{12}=E_{11}$, then $\varepsilon = L_{11}/L_{12}$.
Parameter ε characterizes a technological opportunity to counteract negative weather and its numerical values lay in an interval $0 < \varepsilon < 1$. As a first approximation ε characterize adaptivity of technological processes to the weather forecasts.
Boundary values of parameter have following sense:

$\varepsilon = 0$ - impreventing consequences are absent and protection means are cardinal;

$\varepsilon = 1$ - losses are maximal and cannot be prevented by the meteorological maintenance perfection.

2) The attitude of expenses for protective measures to preventing losses:

$$B = E_{11}/\,[(E_{12}\text{-}E_{11})+L_{12}\text{-}L_{11}]. \tag{14}$$

3) Integrated parameter

$$\beta = \beta_1 + \beta_2 = (1\text{-}B) + (1\text{-}2\varepsilon)/(1\text{-}\varepsilon) \tag{15}$$

characterizes success of financial expenses for protective actions (threshold value of this parameter $\beta = 1$, for $\beta < 1$ the forecast loses economic utility).

4) Parameter of adaptation

$$F= 1 - 2\varepsilon - З_{11}/[(З_{12}\text{-}З_{11})+П_{12}] , \tag{16}$$

The values of this parameter should be positive.

6. THE RESULTS OF THE COMPUTING TESTS

Matrixes of losses for roads I, II and III technical classes with carriageway width 16,5 m, 7,5 m and 7 m accordingly are calculated for one case of ice formation for the road length 1 km in the basic prices of 1991.

6.1 The matrixes of losses for I strategy

Calculations were spent according to the time diagram(fig.2). Losses were defined for cycle time, a general matrix of losses

$$\begin{vmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{vmatrix} = \begin{vmatrix} E_{11} & E_{12} \\ 0 & 0 \end{vmatrix} + \begin{vmatrix} L_{11} & L_{12} \\ 0 & 0 \end{vmatrix} , \tag{17}$$

Some cases were modeled and investigated.

1) <u>Works are spent to cycle time.</u>

The numerical values for roads of various classes, for air temperature -2^0 C and average amount of traffic:

- for roads of I class

$$\begin{vmatrix} 110{,}72 & 110{,}72 \\ 0 & 0 \end{vmatrix} + \begin{vmatrix} 175{,}70 & 175{,}70 \\ 0 & 0 \end{vmatrix} = \begin{vmatrix} 286{,}42 & 286{,}42 \\ 0 & 0 \end{vmatrix}$$

- for roads of II class

$$\begin{vmatrix} 50{,}33 & 50{,}33 \\ 0 & 0 \end{vmatrix} + \begin{vmatrix} 117{,}53 & 117{,}53 \\ 0 & 0 \end{vmatrix} = \begin{vmatrix} 167{,}86 & 167{,}86 \\ 0 & 0 \end{vmatrix}$$

- for roads of III class

$$\begin{vmatrix} 46{,}97 & 46{,}97 \\ 0 & 0 \end{vmatrix} + \begin{vmatrix} 54{,}16 & 54{,}16 \\ 0 & 0 \end{vmatrix} = \begin{vmatrix} 101{,}13 & 101{,}13 \\ 0 & 0 \end{vmatrix}$$

For all matrixes $S_{21} = 0$ as protective actions are not applied and $S_{11}=S_{12}$ as all expenses and losses will be equal (provided that they are observed in cycle time).
For matrixes of losses condition $S_{11} = S_{12}$ is satisfied, so $\varepsilon=1$. It confirms that *protective properties of the consumer are unsatisfactory, of protective technologies are absent, and losses on meteorological conditions are not prevented. Therefore this strategy both theoretically and practically is not "meteosensible".*
In this case it is possible to confirm not only about imperfection of specialized meteorological forecasts, but, in a greater degree, about imperfection of existing road winter maintenance system and technologies.
Thus, despite of sensitivity of management object (road) to weather conditions, even detailed weather forecasts information cannot be realized in decision-making process.

2. <u>Works are spent over cycle time because of special weather forecasts imperfection.</u>

If the time of work more then cycle time, in matrixes of losses one summand remains constant (an expense of the road organizations) and losses will increase:

$$L_{12} = L_{11} + \Delta L \tag{18}$$

A matrix of losses:

$$\begin{vmatrix} S_{11} & S_{12} \\ 0 & 0 \end{vmatrix} = \begin{vmatrix} E_{11} & E_{12} \\ 0 & 0 \end{vmatrix} + \begin{vmatrix} L_{11} & L_{11} + \Delta L \\ 0 & 0 \end{vmatrix} \quad (19)$$

For example, numerical values for road of a I class and for increase work time on 2 hour:

$$\begin{vmatrix} 110{,}72 & 110{,}72 \\ 0 & 0 \end{vmatrix} + \begin{vmatrix} 175{,}70 & 294{,}74 \\ 0 & 0 \end{vmatrix} = \begin{vmatrix} 286{,}42 & 405{,}46 \\ 0 & 0 \end{vmatrix}$$

The analysis of the numerical modeling results has shown, that only when the time is more, then 5 h. this strategy of works gets in a zone of adaptation. This time exceeds normative, that is not supposed by standards.

3. Works are spent in view of the minimal air temperature forecast

Matrixes of losses elements have following sense:

S_{11} - expenses and losses if the road organization use the forecast of slipperiness and the minimal air temperature forecast;
S_{12} - losses and expenses which take place if the road organization does not use forecasts. It spends works, being guided on air temperature in the moment of the works beginning. In this case chlorides "do not work" and it is necessary to add them.

Numerical values of matrixes of losses and parameters of adaptation for roads of various technical classes:

- for roads of I class

$$\begin{vmatrix} 197{,}35 & 221{,}04 \\ 0 & 0 \end{vmatrix} + \begin{vmatrix} 175{,}74 & 349{,}84 \\ 0 & 0 \end{vmatrix} = \begin{vmatrix} 373{,}09 & 570{,}88 \\ 0 & 0 \end{vmatrix}$$

ε=0,31; β=1,06; F=0,04

- for roads of II class

$$\begin{vmatrix} 89{,}71 & 100{,}47 \\ 0 & 0 \end{vmatrix} + \begin{vmatrix} 117{,}55 & 235{,}06 \\ 0 & 0 \end{vmatrix} = \begin{vmatrix} 207.26 & 335.53 \\ 0 & 0 \end{vmatrix}$$

ε=0,35; β=1,05; F=0,03

- for roads of III class

$$\begin{vmatrix} 83{,}72 & 93{,}77 \\ 0 & 0 \end{vmatrix} + \begin{vmatrix} 54{,}18 & 108{,}31 \\ 0 & 0 \end{vmatrix} = \begin{vmatrix} 137{,}90 & 202{,}08 \\ 0 & 0 \end{vmatrix}$$

ε=0,27; β=1,07; F=0,05

Analysis the parameters of adaptation allows to draw a conclusion that this scheme gets in a zone of adaptation. Forecasts of the minimal air temperature allow to receive the certain economic benefit for the road organization and national economy.

6.2 The matrixes of losses for I strategy

Calculations were spent according to the time diagram (fig.3).
The special road forecasts make it possible to use salting procedure to prevent ice formation on the road surface. The spread rate decreases. It is possible to consider preventive works as a protective measure.

Matrixes of losses elements have following sense:

$S_{11} = S_{21}$ – expenses and losses for pre-salting;
S_{12} - expenses and losses for post salting.

Numerical values of matrixes of losses and parameters of adaptation for roads of various technical classes:

- for roads of I class

$$\begin{vmatrix} 38{,}31 & 110{,}72 \\ 38{,}31 & 0 \end{vmatrix} + \begin{vmatrix} 16{,}61 & 175{,}70 \\ 16{,}61 & 0 \end{vmatrix} = \begin{vmatrix} 54{,}92 & 286{,}42 \\ 54{,}92 & 0 \end{vmatrix}$$

ε=0,31; β=1,06; F=0,04

- for roads of II class

$$\begin{vmatrix} 17,42 & 50,33 \\ 17,42 & 0 \end{vmatrix} + \begin{vmatrix} 14,83 & 117,53 \\ 14,83 & 0 \end{vmatrix} = \begin{vmatrix} 32,25 & 167,86 \\ 32,25 & 0 \end{vmatrix}$$

ε=0,09; β=1,49; F=0,72

- for roads of III class

$$\begin{vmatrix} 16,26 & 46,97 \\ 16,26 & 0 \end{vmatrix} + \begin{vmatrix} 7,48 & 54,16 \\ 7,48 & 0 \end{vmatrix} = \begin{vmatrix} 23,74 & 101,13 \\ 23,74 & 0 \end{vmatrix}$$

ε=0,07; β=1,75; F=0,69

Analysis of the calculated matrixes shows, that at pre-icing strategies losses practically are completely prevented and protection measures are cardinal.

6.6 Some results for III and IV strategies

The given technique has allowed to calculate matrixes of losses only for last cycle of snow removal (Fig..4). Precomputations for III and IV strategies have shown, that the parameters of adaptation are near to threshold value. The matrixes of losses were calculated for average parameters of snow intensity and intensity of movement. It is possible to assume, that there are certain combinations of weather and road factors at which parameters of adaptation will exceed threshold values. Besides, practice shows significant preference patrol snow removal and preventive maintenance.

Researches for this strategy will be continued.

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