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Dynamic modeling of winter maintenance strategies and their impact on skid resistance

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Abstract

Snow and ice during the winter period is one of the main factors for low skid resistance resulting in elevated road accident levels and economic cost. Winter maintenance with the application of sodium chloride causes ecological damage due to chloride in road run-off. However these salt application in combination with snow ploughing is, for lack of alternatives, the weapon of choice for road authorities in order to maintain safe roads. The timing and amount of scattered de-icing agents, e.g. sodium chloride, is commonly decided by the winter service vehicle driver based on experience and/or rigid tables. With this common neglect of the variable environmental factors such as traffic intensity, precipitation, surface temperature and gradient, suboptimal results are very likely. Based on an intense research program and statistical analysis funded by all regional and national road authorities in Austria, a model to simulate the impact of these factors on skid resistance was developed. The key factor is the determination of the residual salt depending on traffic and precipitation over time, resulting in an increased freezing point of water on the road. The goal of salting is to lower the freezing point of the brine on the road below surface temperature, thus preventing freezing with significantly lowered skid resistance. Based on the presented model, it is possible to simulate the impact of winter maintenance and optimize the timing and amount of applied de-icing agents under any condition over time. Excessive or unnecessary treatments can be detected in the simulation process and therefore be eliminated by specific instructions leading to optimized winter maintenance with decreasing costs, ecological damage and consumption of resources without lowering the level of safety.

Keywords: Winter maintenance; modelling; skid resistance; safety; resources

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1. Introduction

The number of road accidents in winter period is directly connected to reduced skid resistance due to snowfall, hoarfrost or black ice. Hoarfrost or black ice tend to occur locally giving the unprepared driver less possibility to recognize the slippery road conditions in time for an appropriate speed reduction. Winter maintenance is an established and proven way to minimize the risk of accidents during winter period and therefore indispensable for people and economy in regions where snowfall and temperatures below 0°C occur.

The cost of winter maintenance accounts for roughly 20 to 25 % of total maintenance budgets on Austrian highways and 50% on Canadian Highways (Buchanan, 2005). The benefit of winter maintenance for economy as a result of time savings, reduced injuries and deaths on the road has been proven several times higher (Bark et al., 1995; Klotz et al., 2004; Usman, 2010). Hence the costs of winter maintenance are way below the benefits for the economy. Furthermore the application of an average of 7.5 tons sodium chloride applied per lane kilometer and year in Austria (Hoffmann et al., 2011) is likely to affect roadside plants (Blomqvist, 1999), soil, groundwater and nearby rivers (Ramakrishna, 2005). Another drawback of salting are metal corrosion on cars, bridges and other road assets. An optimization of the salt rate therefore is crucial in order to avoid unnecessary environmental damage due to excessive winter maintenance.

Modeling the physical processes occurring in winter maintenance with the key factors skid resistance and road condition allows an estimation of the optimal application rate depending on weather forecast, traffic volume and road texture. Further considerations including the sensitivity of the receiving environment on the optimal application rate were not scope of this research. Simple application rate tables as explained in some country reports cited in (PIARC, 2010) only consider air temperature, more advanced ones count in the importance of roads, precipitation type and temperature ranges (FGSV, 2010). These tables have to be kept simple in order to be used by winter maintenance personal. Since simple tables are very rigid and advanced ones open the way for misinterpretation the resulting application rates are suboptimal and the acceptance of these tables is low. Most existing winter maintenance models however specialize on one particular element or don´t consider important factors such as precipitation rate or road condition. The presented model goes beyond these approaches towards a prediction of skid resistance as the key factor of road safety.

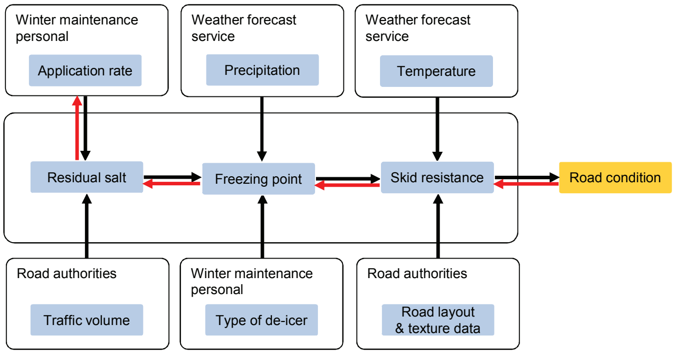

Fig. 1. Schema of a model describing on-going physical processes during winter maintenance in order to estimate road conditions according to several factors.

The model shown in Figure 1 considers all main factors and allows an estimation of road conditions due to a chosen application rate under specific weather conditions, traffic volume and road layout. The applied salt is reduced due spreading losses and traffic. Residual salt and precipitation form a brine on the road with a decreasing concentration. The comparison of road surface temperature and brine freezing point depending on brine concentration and type of de-icer shows the risk of snow or ice on the road. For accurate results of the model the given road layout and surface texture are taken into account as well. In Austria existing data from continuous condition survey with the RoadSTAR-system (Gruber, 2004) can be used in the model. For any simulation the road is divided into individual sections that are specified as mentioned above allowing a separate simulation of each section.

2. Determination of residual salt

Using de-icers to prevent slippery roads makes the actual amount of de-icer on the road one of the main factors to evaluate road safety in the presented model. Since NaCl is the favored de-icer used on roads the model starts with residual salt estimation in the wheel track. Past and recent studies (Zulauf, 1965; Hausmann, 2010) give a clue on the high salt losses in a short period after the application but do not provide enough data for a statistical analysis. In order to provide high quality estimations on residual salt needed in the model extensive field tests took place during winter 2010/11 both on highways and regional roads with less traffic volume.

The amount of salt has been determined using the “Salt Quantity Meter SOBO20” fabricated by Boschung mechatronic which allows high numbers of measurements in short time due to its easy handling. Each residual salt value is the arithmetic mean of five measurements located in the right wheel track of the first lane. The measurements were timed right before and after salt application in order to compare the applied amount with the appointed amount. The further decrease was measured 30, 60, 90, 120, 240 and 480 minutes after application. All salt spreaders used in the field tests were calibrated before the winter season and used pre-wetted spreading technology with a 3:7 ratio of brine to dry salt.

The goal was set to evaluate the influence of traffic volume, speed, gradient, road texture and precipitation rate on the decrease of residual salt. Even after 350 measurements the data is not fully sufficient to evaluate each factor. However there is enough data to point out the massive initial losses and give an estimation of residual salt depending on traffic volume under dry, moist or wet road conditions. Due to a lack of measurement equipment on most measuring spots at this stage of research the road conditions in the wheel tracks were visually separated in three categories.

About 60 % of the appointed amount of salt is carried out of the wheel tracks within the first 10 minutes respectively 100 cars as shown in Figure 2a. These initial losses are caused by strong air movements above the road due to the impact of winds or passing vehicles. Traffic and precipitation induce run-off or spray responsible for further losses of residual salt, shown in Figure 2b with the residual salt after initial losses as allocation base and the decisive factor traffic volume. On wet roads after 2,000 Vehicles almost all residual salt is gone, while on dry or moist roads even after 8,000 there still is an amount of 1 to 5 g/m² salt left on the road.

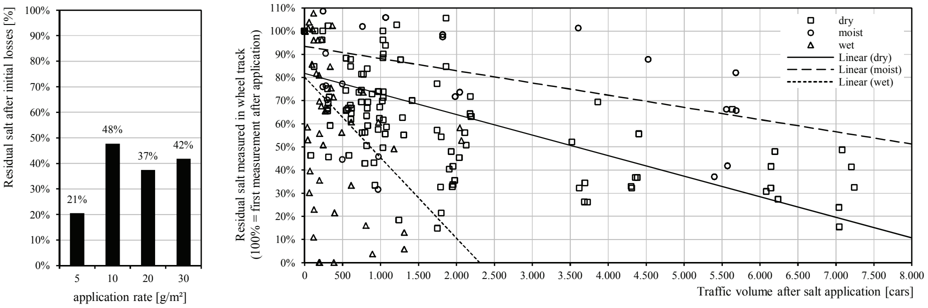

Fig. 2. (a) Initial salt losses after application; (b) Residual salt on the road depending on traffic volume

In the modeling process residual salt (RS) on a road is estimated using Formula 1a for dry conditions, appearing mostly at preventive spreading, Formula 1b for moist conditions e.g. hoarfrost and Formula 1c for wet conditions in case of precipitation. Initial losses are taken into account with 60 % of the application rate (AR), the declining factor is traffic volume (TV) in the reviewed period. Separating the initial losses from traffic induced losses provides higher accuracy and flexibility in the choice of describing functions for long term estimations. Functions for the whole process tend to underestimate the residual salt in the surface texture after more than 4.000 cars, especially when low salt rates are used.

$$RS = AR*0.4*(-0.00009 * TV + 0.8171) \text{ (dry road, } R^2=0.4437) \quad (1a)$$

$$RS = AR*0.4*(-0.00005 * TV + 0.935) \text{ (moist road, } R^2=0.2718) \quad (1b)$$

$$RS = AR*0.4*(-0.0003 * TV + 0.8009) \text{ (wet road, } R^2=0.2048) \quad (1c)$$

3. Calculating the freezing point of brine on the road for different de-icing agents

The amount of residual salt alone is no indicator of the risk of icy roads, rather the freezing point of the brine emerged out of precipitation and residual salt has to be compared to the road surface temperature. Since there are several good road surface temperature forecast models (NCAR, 2007) the surface temperature is considered an input parameter in the presented model. The precipitation film (PF) on the road can be estimated according to (Hausmann, 2009) with Formula 2a using precipitation rate (RR) as basis for a dry up mechanism due to traffic volume (TV) and wind speed (W). At this stage precipitation is calculated based on an equivalent amount of water. The different behavior of snowfall consistency and density will be addressed in further in-depth field research. Along with precipitation hoarfrost (HF) is a source for ice/water on the road and can be estimated using wind speed (W), temperature (T) and the difference between actual vapor pressure and saturation vapor pressure (D) using Formula 2b (Hausmann, 2009).

$$PF = (RR + HF)*e^{-TV*(0.005+0.001*W)} \quad (2a)$$

$$HF = 2,16*10^{-6}*W*D/T \quad (2b)$$

With knowledge of residual salt and the amount of water on the road the concentration of the formed brine on the road is calculated in the model in order to determine the freezing point. For common de-icers the freezing point is lower at higher concentrations up to the eutectic point where despite further raise of concentration the freezing point stays at a temperature level. The correlation has been analyzed for the common de-icing agents sodium chloride, calcium chloride and magnesium chloride, establishing freezing point curves as shown in Figure 3. The mathematical description in Formula 3a for sodium chloride, Formula 3b for calcium chloride and Formula 3c for magnesium chloride allows a determination of the freezing point (FP) based on the brine concentration (BC).

$$FP_{NaCl} = -0,001866 * BC^3 + 0,03995 * BC^2 - 0,8580 * BC - 0,3169 \quad (3a)$$

$$FP_{CaCl} = -0,001120 * BC^3 - 0,007779 * BC^2 - 0,4046 * BC - 0,3845 \quad (3b)$$

$$FP_{MgCl} = -0,002421 * BC^3 - 0,000354 * BC^2 - 0,5510 * BC - 0,4077 \quad (3c)$$

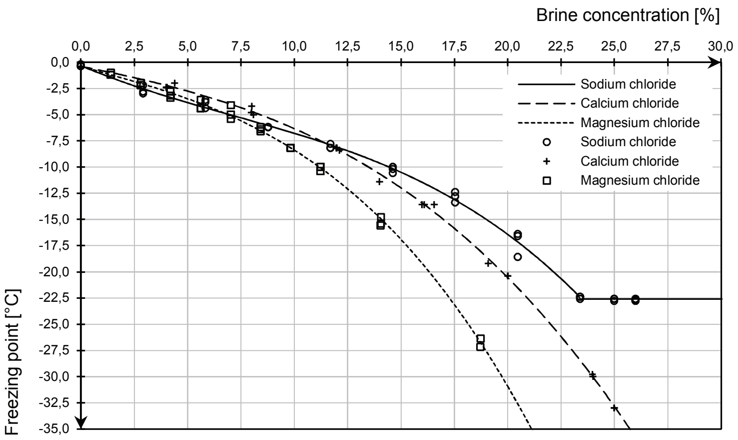

Fig. 3. Brine concentration - Freezing point diagram for sodium chloride, calcium chloride and magnesium chloride on the basis of freezing experiments with fitted freezing curves.

Sodium chloride has further benefits due to the fact that calcium chloride and magnesium chloride are three to five times more expensive and unsuitable for dry salt spreading as a result of their high hygroscopicity. In Austria Safecote as an additive to sodium chloride brine has been tested over the last few years by several road authorities. The characteristics of sodium chloride, calcium chloride, magnesium chloride and Safecote differ in corrosion, environmental impact, thawing capacity and costs. Given that they only appear as brine component in prewetted salt application and only represent 4 % to 10 % of the whole application rate using the common brine to salt ratio 3:7 the influence of their characteristics over the dominating sodium chloride is low. Making up only the marginal part of about 7 % of the whole spreading material they raise the price by 12 % to 18 % compared to sodium chloride brine with 20 % concentration.

4. Film thickness and skid resistance

The area available for vertical and horizontal force transmission is limited to the small contact area of tire and road. An interruption of the contact due to a medium leads to a decrease in transmittable force and therefore in skid resistance. If a medium is liquid, it fills up the road surface texture as shown in Figure 4 reducing contact area and skid resistance depending on the relation of medium volume and texture volume. In respect of winter maintenance precipitation in form of rain or snow as well as ice are relevant mediums.

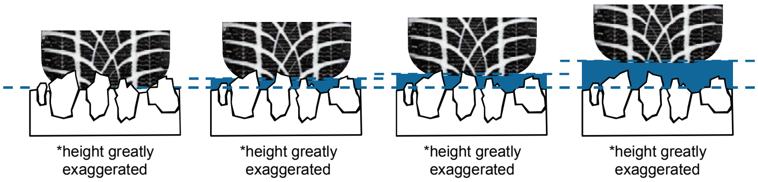

Fig. 4. Reduced contact area tire-road due to filled texture volume

Recent studies (Hoffmann et al., 2011) using the skid resistance testing device GripTester MKII and Vaisala DSC 111 remote surface state sensors point out the thin line between sufficient skid resistance and slippery roads. If the road texture is filled with snow or ice ploughing and salting raises skid resistance only for a short period until persistent snowfall lowers it again. However, until road texture is entirely filled skid resistance remains at a high level giving winter maintenance personal a time buffer to initiate preventive spreading. The duration of the time buffer until skid resistance drops below a certain threshold of $\mu = 0.4$ depends on snowfall rate and available texture volume. For a typical asphalt road the time buffer is about 30 to 45 minutes at a common precipitation rate of 0.5 mm/h.

The correlation between filled texture volume and wetted surface has been reviewed using a chromatic white laser for a 3D topography measurement on 6 sample cores in laboratory tests. Figure 5a shows cores A10_G1 and A10_G6 taken from rigid pavements have a considerable higher texture volume than the others taken from flexible pavements. The skid resistance drops suddenly with almost filled textures when small quantities of snow are enough to cover up the remaining road surface. The correlation of asphalt samples (A21_AA, A21_CB, A21_DC, A10_G4) with 80% of the volume filled and only 20% wetted surface illustrate the time buffer and sudden drop in skid resistance. To wet the remaining 80 % surface only 20 % of the total texture volume is needed.

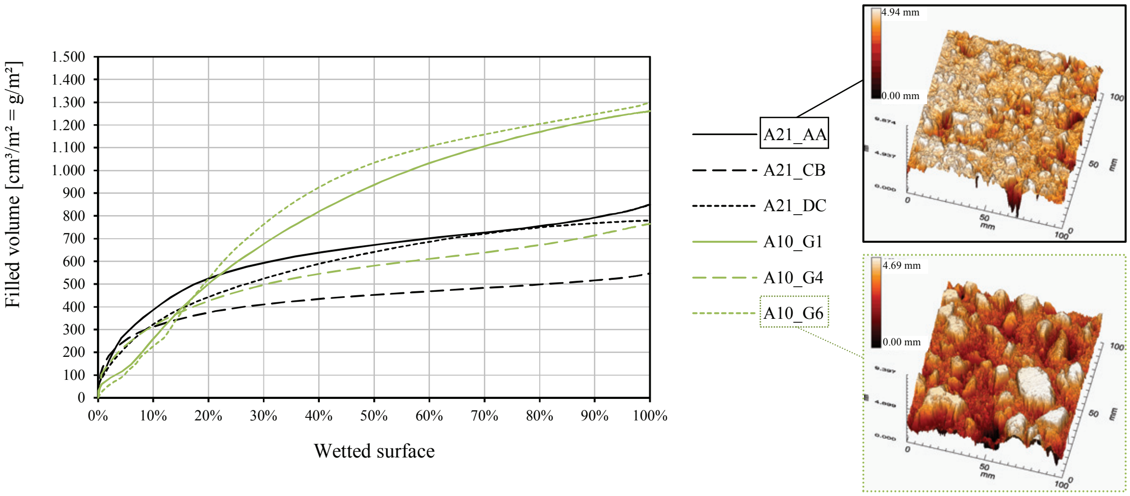

Fig. 5. (a) Correlation: Filled volume – Wetted surface for 6 sample cores. (b) Topography laser scans of cores A10_G6 and A21_AA

Laboratory experiments using a SRT-Pendulum show that in wet conditions skid resistance drops already at a small amount of water on the sample core. Field tests (Maurer, 2007) showed comparable results with dropping skid resistance from 0 to 0.04 mm and further stagnation up to the maximum range of 1 mm. For the laboratory experiments the texture of 6 sample cores was filled to 25%, 50% 75% and 100% with 3 different types of brine respectively water. The difference between the brines in the relative drop on basis of dry samples shown in Table 1 is not significant, confirming the field tests.

Table 1. Reduced SRT-Values due to brine respectively water in relation to dry sample cores (Mean dry SRT-Value = 100%) (mean of 6 sample cores, each tested 5 times)

Fluid-filled texture volume:	0%	25%	50%	75%	100%
Water	100%	70%	62%	60%	58%
Sodium chloride brine 20%	100%	60%	55%	54%	54%
Calcium chloride brine 23%	100%	54%	52%	51%	49%
10% Safecote 90% NaCl-brine (20%)	100%	55%	55%	54%	53%

If the freezing point of the fluid on the road is below road surface temperature, the precipitation on the road surface is liquid and skid resistance is lowered to the level of a wet road surface under usual measurement conditions. Only in case of snow or ice the skid resistance in the model is lowered using reference values based on the relative ratio of precipitation film to road surface texture. Continuous Road Safety Inspections on Austrian highways and other high level country roads provide the necessary data concerning mean texture depth and estimated texture depth for each road section. Together with close-mesh weather forecasts the model allows a prediction of skid resistance on all parts of the highway network based on the selected winter maintenance strategy.

5. Road conditions, time savings and costs

If precipitation on the road is liquid, the skid resistance level in general is high enough to maintain safe roads without further consideration and the road condition is set to 1 (very good). Mandatory planning parameters (e.g. curve radius) for new roads in Austria ensure a safe ride under road conditions 1 and 2. Road conditions 2 (good), 3 (moderate) and 4 (poor) vary in filled volume according to Table 2. Road condition 5 (very poor), with a snow layer of more than 2 cm is the worst case scenario given the model is mainly used on highways with strict requirements on winter maintenance and the snowfall rate rarely exceeds 2 cm/h.

The costs of winter maintenance are calculated using typical costs for personal, equipment and de-icer. Since costs vary for each road authority only individual costs should be used for the optimization of winter maintenance costs for larger road networks. To calculate the benefit of winter maintenance, time savings emerging from better road conditions are used. Time savings are estimated using the speed limit as base and lowered speed for each road condition according to (Bark et al.,1995) for trucks and (Cypra, 2007) for cars. Emerging additional journey time needed to pass the reviewed sections is calculated for each time step and condition. The summarized time losses for both cars and trucks passing the simulated section in the reviewed period are an output value for further considerations.

The transformation of time into money is taken into account with 30 €/h for business travelers, 8 €/h for private persons and 82 €/h for trucks according to Regulation Nr. 02.01.22 (RVS) from 2010. The estimation of accident costs with the presented model is also feasible but not yet implemented.

Table 2. Road condition and speed depending on possible freezing, filled volume, wetted surface and snow layer thickness

Road condition	Freezing	Filled volume	Wetted surface	Snow layer	Speed Cars	Speed Trucks
1 - very good	No	-	-	-	100%	100%
2 - good	Yes	< 60%	< 20%	-	92%	97%
3 - moderate	Yes	< 90%	< 80%	-	82%	90%
4 - poor	Yes	> 100%	> 100%	< 2cm	77%	79%
5 - very poor	Yes	> 100%	> 100%	> 2cm	50%	50%

6. Example simulation for a single highway maintenance depot

The first simulations of different winter maintenance strategies on a highway section with typical regional weather scenarios show the possibilities of the presented model. The reviewed section is 175 lane kilometers long with 2 respectively 3 lanes per direction. The typical weather scenario is chosen with snowfall from 07:00 am to 3:00 pm at a constant snowfall rate of 0.5 cm/h (equals 0.5 mm/h water) and hoarfrost in the early morning the next day. The calculated road conditions with and without treatment are compared in figure 6.

As reference a usual treatment is simulated, using 6 trucks an application rate of 20 g/m² in two treatment cycles starting 30 minutes after the beginning of the snowfall event and another treatment at shift change (7:00 pm) is used. In these reference scenario 146 tons of salt were used, the total costs add up to 12,157 € with total time savings of 146 h for Cars and 34 h for trucks.

The chosen typical weather scenario however allows road authorities to maintain better road conditions using higher application rates and adjust the time of treatments. The amount of salt needed to provide road condition 1 almost all the time is 255 tons, almost double the number using the reference strategy. Doubling the amount of salting raises total winter maintenance costs only by 57 % to 19,981 € due to fixed costs for personal and equipment. The time savings are almost doubled to 289 h for cars and 63 h for trucks.

A more environmental friendly strategy with only 4 treatments at an application rate of 15 g/m² and a total salt consumption of 73 tons completes the given examples. In Figure 6c no road condition improvement can be seen due to the very small time steps they occur. However there are time savings of 46 h for cars and 11 h for trucks at maintenance costs of 6,900 €.

Depending of the importance of the road and the available resources the model provides road authorities with the means to compare different winter maintenance strategies and their results. If economic benefits based upon time savings are calculated the environmental costs due to pollution may be taken into account as well and will be included in further versions of the presented model. According to (NRCan, 2012) every ton salt applied on the road produced 7.9 kg of CO2 in production. Thus a treatment with 20 g/m² on a 3.5 m wide road resulting in a CO2 emission of 553 g/km which is more than 4 times higher as the CO2 emission limit for new cars proposed by the European commission in COM(2007) 856.

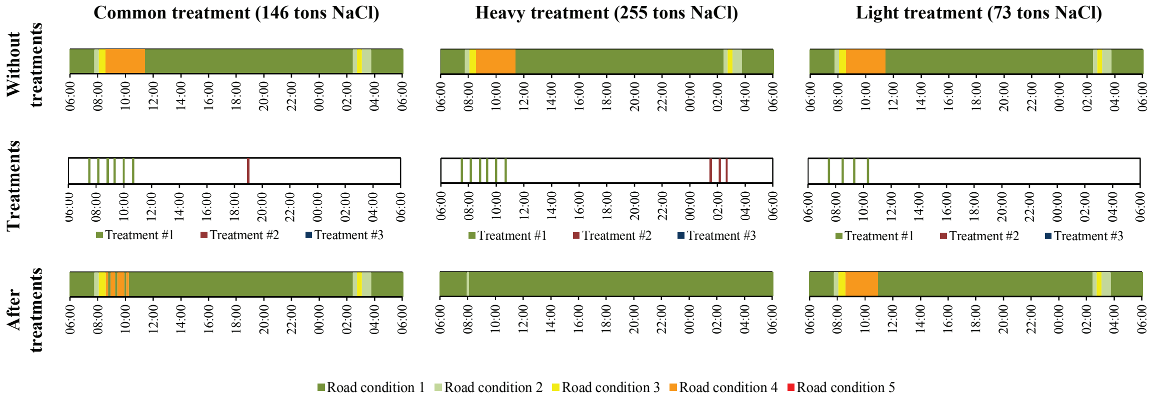

Fig. 6. Road conditions zero option, treatments and improved road conditions due to winter maintenance for (a) common strategy; (b) heavy treatment; (c) light treatment

7. Conclusion and Outlook

The presented winter maintenance model allows an appraisal of road conditions for any weather forecast or user-defined weather scenario using variations of treatment intervals, application rates and de-icing agent types to find the optimal treatment strategy under any given boundary conditions or restrictions. At this stage factors e.g. precipitation film thickness show some variation in the actual model with the need for further research in order to achieve a more robust fitting. However, all other factors have already been verified and show promising results.

Typical situations in winter maintenance have been simulated and findings have been discussed with seasoned winter maintenance personal. The outputs of the modules residual salt, freezing point and skid resistance are in line with practical experience and the results of field and lab – testing and can therefore be considered safe for practical use.

The theoretical background of the model has been wrapped into a user friendly winter maintenance handbook for practical use. Winter maintenance personal has been involved in the development of the model and was trained with simplified model outputs and physical basis of winter maintenance. A key factor is the need for a preventive treatment due to salt losses depending on traffic volume. Tables for salt application rate depending on road surface temperature, traffic volume and precipitation rate were developed as well. Furthermore the costs and benefits of different brines were compared and recommendations are given depending on region and existing winter maintenance resources.

For both winter maintenance personal and road users specific recommendations for five typical weather scenarios were developed. The weather scenarios were chosen with skid resistance as key factor and visualized with photos for easy recognition (Hoffmann, 2011).

With the simulation of winter maintenance the resulting road conditions, costs, and benefits offer road authorities the opportunity for an optimization of their common treatment strategies. The model may be implemented to almost any road network without sufficient additional effort since most factors e.g. AADT, road layout and texture are already known. Environmental consequences can be determined more exactly using road and drainage layout, common regional weather conditions and amount of salt in run off or spray.

If the simulation results are calibrated with data from real time measuring devices on the road the stochastic variation in the calculated results can be reduced even further. If the model outputs are communicated on-line to the winter maintenance personnel further improvements in salting and winter maintenance are possible.

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