10.6 AUTOMATED FORECASTING OF ROAD CONDITIONS AND RECOMMENDED ROAD TREATMENTS FOR WINTER STORMS*

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1. INTRODUCTION*

Over the past decade there have been significant improvements in the availability, volume, and quality of the sensors and technology utilized to both capture the current state of the atmosphere and generate weather forecasts. New radar systems, automated surface observing systems, satellites and advanced numerical models have all contributed to these advances. However, the practical application of this new technology for transportation decision makers has been primarily limited to aviation. Surface transportation operators, like air traffic operators, require tailored weather products and alerts and guidance on recommended remedial action (e.g. applying chemicals or adjusting traffic flow). Recognizing this deficiency, the FHWA (Federal Highway Administration) has been working to define the weather related needs and operational requirements of the surface transportation community since October 1999.

A primary focus of the FHWA baseline user needs and requirements has been winter road maintenance personnel (Pisano, 2001). A key finding of the requirements process was that state DOTs (Departments of Transportation) were in need of a weather forecast system that provided them both an integrated view of their weather, road and crew operations and advanced guidance on what course of action might be required to keep traffic flowing safely. As a result, the FHWA funded a small project (~$900K/year) involving a consortium of national laboratories[1] to aggressively research and develop a prototype integrated Maintenance Decision Support System (MDSS). The prototype MDSS uses state-of-the-art weather and road condition forecast technology and integrates it with FHWA anti-icing guidelines to provide guidance to State DOTs in planning and managing winter storm events (Mahoney, 2003).

The overall flow of the MDSS is shown in Figure 1. Basic meteorological data and advanced models are ingested into the Road Weather Forecast System (RWFS). The RWFS, developed by the National Center for Atmospheric Research (NCAR), dynamically weights the ingested model and station data to produce ambient weather forecasts (temperature, precipitation, wind, etc.). More details on the RWFS system can be found in (Myers, 2002).

Next, the RCTM (Road Condition Treatment Module) ingests the forecasted weather conditions from the RWFS, calculates the predicted road conditions (snow depth, pavement temperature),

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estimates recommended treatments and forecasts the effectiveness of those treatments.

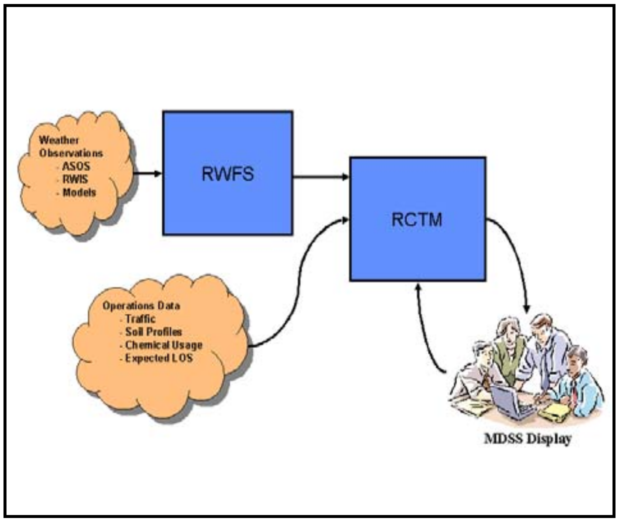

Figure 1. Overview of MDSS system.

Once a treatment plan has been determined, the recommendations are presented in map and table form through the MDSS display. The display also allows users to examine specific road and weather parameters, and to override the algorithm recommended treatments with a user-specified plan.

A brief test of the MDSS system was performed in Minnesota during the spring of 2002. Further refinements were made and an initial version of the MDSS was released by the FHWA in September 2002. While this basic system is not yet complete, it does ingest all the necessary weather data and produce an integrated view of the road conditions and recommended treatments. This paper details the RCTM algorithm and its' components, including the current and potential capabilities of the system.

2. RCTM OVERVIEW

A key component of the MDSS, and the focus of this paper, is the Road Condition and Treatment Module (RCTM). The RCTM is designed to bridge the gap between ambient weather forecasts (temperature, precipitation, wind, etc) and road condition forecasts (pavement temperature, snow depth, mobility, etc.) and ultimately to make recommendations for chemical applications and/or snow plowing to keep the roads above a minimum level of service. The RCTM consists of five main components as shown in Figure 2: road snow depth, pavement temperature, road mobility, chemical concentration and rules of practice (recommended treatments). The components range from slight modifications of existing algorithms (SNTHERM for pavement temperature) to newly developed algorithms for mobility and rules of practice. Most of the algorithms are in their infancy, capturing only the basic elements of the processes. The system is designed modularly, allowing future developers and/or vendors to modify or replace these baseline components.

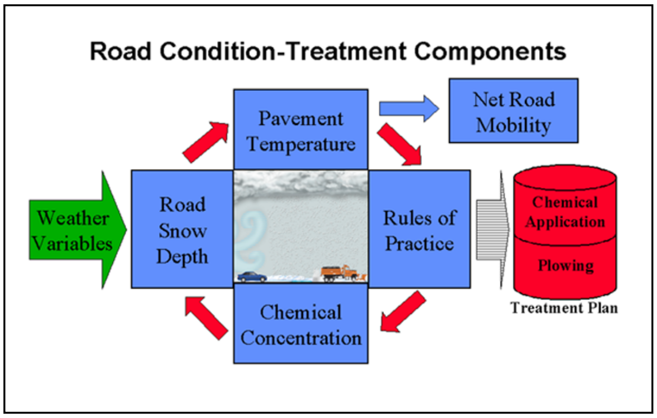

Figure 2. Road Condition Treatment Module flow diagram.

Unlike numerical weather models or the RWFS portion of the MDSS, the RCTM components interact with one another. Initial assessments of snow depth and pavement temperature are modified when a treatment is applied. Similarly, the additional treatments are affected by the modified pavement temperatures and snow depths. Currently, the RCTM iterates to update the road conditions and chemical concentrations each time a new treatment is defined.

3. ROAD SNOW DEPTH

The depth of the snow or ice on the road surface is obviously an important trigger for winter maintenance operations. As shown in Figure 3, the initial (untreated) snow depth is primarily a function of the water content of the snow that is falling and the pavement temperature of the road surface. Once a chemical treatment is applied, the snow on the road (de-icing) and/or any falling snow landing on the road (anti-icing) will turn to liquid at

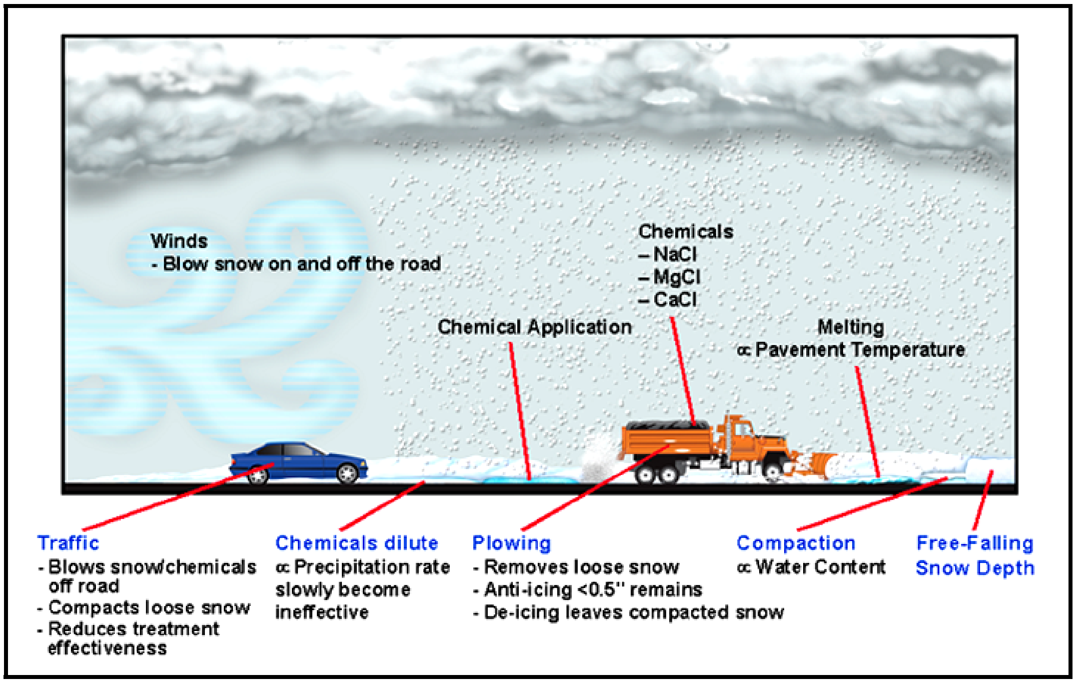

Figure 3. Estimating snow depth before and after treatment.

least to the extent that the treatment is effective. In addition, plowing operations will drop the snow depth to minimal levels (snow plow blade completely removes snow from the road surface). In the case of de-icing operations, the snow may become compacted and bonded to the pavement. Finally, winds may cause the snow to blow on and off the road depending on orographic effects.

Although snow depth is identified in Figure 2 as an individual process, snow depth calculations are spread out over multiple RCTM components. The RCTM driver currently converts liquid precipitation rates into snow depths using a nominal 10:1 ratio of snow to water. The Pavement Temperature model handles the compaction and melting of snow due to the thermal properties of the road. The Chemical Concentration algorithm passes back chemical effectiveness to the RCTM that in turn converts snow to water during hours of effective melting. Finally, the Rules of Practice module may recommend plowing, causing the RCTM to set the snow depth to minimal levels. There is currently no provision in the snow depth calculations for the impact of winds or traffic.

4. PAVEMENT TEMPERATURE

The key aspect of the RCTM is the ability to predict road surface conditions as a function of forecasted weather. For surface transportation, the most important road surface condition is road surface temperature, which impacts the application of chemicals used to clear snow and ice, and the prediction of the road snow cover depth. A modified version of the mature and extensively validated model SNTHERM 89, called SNTHERM-RT, uses the road base, pavement, and the atmospheric boundary conditions to calculate the road/atmosphere energy balance (Jordan, 1991). SNTHERM-RT, assumes the road moisture content is zero. Therefore, the latent heat exchange between the road and the overlying atmosphere is not part of the road/atmosphere energy balance. But, rain and snow are permitted to accumulate on the road surface and the exchange of latent heat between the layer of either water or snow on the road surface and the atmosphere is modeled. Output from this model, pavement temperature, together with the type and phase of precipitation falling (from RWFS module) and the binned conditions provided in the Road Mobility module, allow the user to determine if pavement conditions are above or below allowable levels. Forecasted weather, as input to SNTHERM-RT, ultimately produces forecasted road conditions that allow one to determine when in the course of a storm vehicle mobility will reach unacceptable levels.

Unlike soils and snow covers, many of the thermal and optical properties of road surface materials (asphalt and concrete) may not be readily available to the MDSS user of SNTHERM-RT. To accommodate this, these properties have been tabulated from values found in the literature.

SNTHERM-RT is currently only in the validation phase. A heavily instrumented outdoor test site, including two asphalt pads, a concrete pad, and non-paved (bare ground) section, has been established to determine the model's strengths and weaknesses.

5. ROAD MOBILITY

Winter maintenance personnel expressed a desire to have a single metric to measure the ability of traffic to flow normally along a route given the current and forecasted weather conditions. For example, a road of sheer ice would have the same low score as a road with 20 inches of snow. In both cases traffic cannot move at all. The metric would be useful in defining both a road's required level of service and the effectiveness of treatment recommendations and actions.

This metric, while potentially very useful, will require a concerted research effort that is outside the scope of the initial MDSS deployment. The MDSS does include a "Net Mobility Index" that calculates an index based on the general pavement condition (Table 1). In the future, the mobility index may be used to trigger treatment options. However, further discussions with users will be needed to refine the definition and uses of an enhanced mobility index.

Table 1. Mobility Index as a function of pavement condition.

Pavement Conditions	Mobility Index
Dry	0.9
Wet	0.7
Snow < 4 inches	0.6
Snow 4-6 inches	0.4
Snow > 6 inches	0.3
Ice	0.2

6. RULES OF PRACTICE

The Rules of Practice (ROP) component is designed to recommend appropriate road treatment actions (chemicals, plowing) to keep the road conditions above the recommended level of service. Winter maintenance personnel typically have a variety of treatment options available to them. The treatment path chosen is affected not only by the weather and road conditions but also by the availability of equipment and chemicals, environmental factors and the required level-of-service (LOS) of the road being treated.

Level-of-service refers to the desired condition of the road during and after the storm. Major roadways with high volumes of traffic will often have a bare pavement LOS (no snow/ice). Secondary roads may have snow-covered or <1 inch thresholds, and rural roads generally have much higher thresholds. Once an LOS has been set, the next critical decision is whether to perform anti-icing or de-icing operations. Anti-icing refers to a snow and ice control practice of applying chemicals to prevent the formation or bonding of snow and ice to road surfaces. Treatments are often applied in advance of the actual storm event so that the initial snow/ice does not form a strongly bonded layer on the road surface. This method is more likely to be used when the LOS is bare pavement. Conversely, de-icing refers to the practice of combating the storm as it happens -- plowing and applying chemicals to minimize snow and ice build-up. The Rules of Practice algorithm embraces the concept of anti-icing, but also recognizes that some storm conditions (overwhelming snow) or circumstances (equipment breakdown, inadequate crew availability) may necessitate de-icing operations.

The automated guidance in ROP is based on anti-icing guidelines developed by CRREL for the FHWA (FHWA, 1996). CRREL derived these recommended treatments by examining the effectiveness of chemical treatments during actual winter storms in a variety of states. The FHWA guidelines present treatment recommendations as a series of tables for generic storm types; an example for a light snowstorm is shown in Figure 4. Maintenance crews use their preferred weather forecast (TV, NWS, RWIS) to predict the pavement temperature range over the next few hours. Based on this estimate of the pavement temperature and user

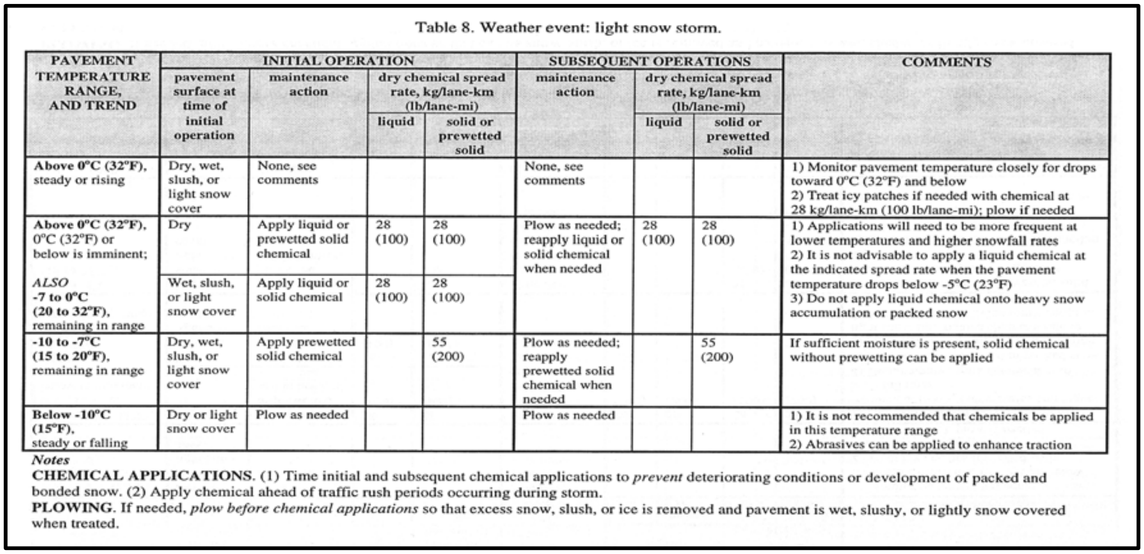

Table 8. Weather event: light snow storm.

PAVEMENT TEMPERATURE RANGE, AND TREND	INITIAL OPERATION				SUBSEQUENT OPERATIONS			COMMENTS
	pavement surface at time of initial operation	maintenance action	dry chemical spread rate, kg/lane-km (lb/lane-mi)		maintenance action	dry chemical spread rate, kg/lane-km (lb/lane-mi)		
			liquid	solid or prewetted solid		liquid	solid or prewetted solid	
Above 0°C (32°F), steady or rising	Dry, wet, slush, or light snow cover	None, see comments			None, see comments			1) Monitor pavement temperature closely for drops toward 0°C (32°F) and below 2) Treat icy patches if needed with chemical at 28 kg/lane-km (100 lb/lane-mi); plow if needed
Above 0°C (32°F), 0°C (32°F) or below is imminent; *ALSO* **-7 to 0°C (20 to 32°F),** remaining in range	Dry	Apply liquid or prewetted solid chemical	28 (100)	28 (100)	Plow as needed; reapply liquid or solid chemical when needed	28 (100)	28 (100)	1) Applications will need to be more frequent at lower temperatures and higher snowfall rates 2) It is not advisable to apply a liquid chemical at the indicated spread rate when the pavement temperature drops below -5°C (23°F) 3) Do not apply liquid chemical onto heavy snow accumulation or packed snow
	Wet, slush, or light snow cover	Apply liquid or solid chemical	28 (100)	28 (100)				
-10 to -7°C (15 to 20°F), remaining in range	Dry, wet, slush, or light snow cover	Apply prewetted solid chemical		55 (200)	Plow as needed; reapply prewetted solid chemical when needed		55 (200)	If sufficient moisture is present, solid chemical without prewetting can be applied
Below -10°C (15°F), steady or falling	Dry or light snow cover	Plow as needed			Plow as needed			1) It is not recommended that chemicals be applied in this temperature range 2) Abrasives can be applied to enhance traction

Notes

CHEMICAL APPLICATIONS. (1) Time initial and subsequent chemical applications to *prevent* deteriorating conditions or development of packed and bonded snow. (2) Apply chemical ahead of traffic rush periods occurring during storm.

PLOWING. If needed, *plow before chemical applications* so that excess snow, slush, or ice is removed and pavement is wet, slushy, or lightly snow covered when treated.

Figure 4. Example table from FHWA anti-icing treatment guidelines.

estimates of the prevailing road conditions (dry, wet, slush, etc), the operator selects the appropriate treatment from the series of tables. For example, from Figure 4, a light snowstorm with pavement temperatures between -10 and -7 degrees C and wet road conditions would yield a recommendation to apply pre-wetted solid chemicals at a rate of 200 lbs/lane-mile.

Automated treatment recommendations in the ROP are implemented as a series of curves (derived from the FHWA guidelines) relating pavement temperature to chemical application rate. The Rules of Practice chemical treatment diagram for salt is shown in Figure 5. The nominal treatment rate represents the recommended treatment rate for a moderate snowfall (0.5 inch/hour). Lighter amounts of snow shift this curve downward and heavier amounts shift it upward. The nominal precipitation type is snow; the slope of the curve is adjusted upward (proportionally heavier amounts of chemicals are needed at cooler temperatures) as the precipitation type moves toward freezing rain (snow->mixed->sleet->freezing rain). Each chemical has a preferred temperature range, for salt this range is from -10 to 0 degrees C. Below this range, only plowing is recommended because the salt would not be capable of melting any precipitation that falls, thus wasting the chemical and reducing mobility on the road. Above the temperature range, chemicals become increasingly unnecessary as the thermal heating from the road naturally prevents ice/snow from bonding to the road surface.

The algorithm makes recommendations about if, when and how much chemical to apply. Each time the algorithm is invoked it searches the road forecast data for a treatment trigger. The primary trigger is the presence of a minimal amount of snow or ice on the road surface. Once this primary trigger is found, treatment is estimated over the time it would nominally take to service the route. Precipitation type and rate are combined with pavement temperatures to extract a treatment rate from the curves discussed above. If treatment is recommended, then the action is passed back to the RCTM and used to update the expected road conditions. If no treatment is recommended then the process continues to the next hour. A secondary trigger for plowable snow (nominally 3 inches) will result in a recommendation to plow the route. Freezing rain, to the extent that it builds up on the road surface, will also trigger the treatment estimation process.

The user selects a preferred chemical type; the algorithm currently does not automatically evaluate the pros and cons of all the possible de-icing chemicals. This algorithm is only a first step towards a fully automated guidance system; many simplifications have been made to make this initial task more manageable. The initial focus has been on incorporating a simplified treatment recommendation system into the MDSS that allows the

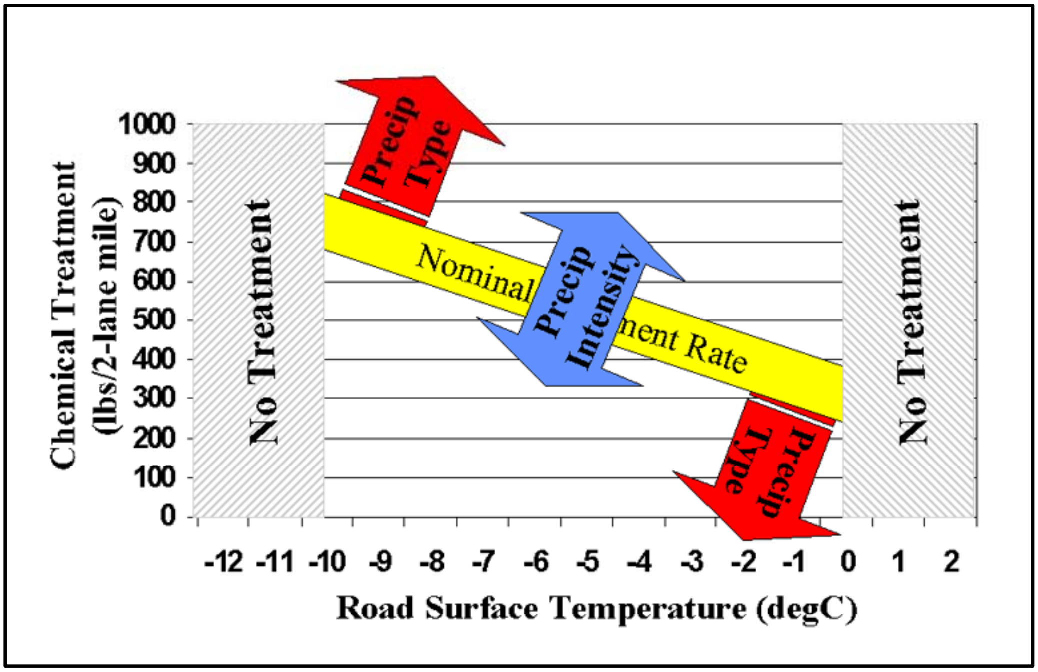

Figure 5 Illustration of how salt treatment recommendations are calculated in the Rules of Practice

automated ingest of road and ambient weather forecasts.

Integrating the Rules of Practice into the MDSS produces several benefits. First, pavement temperature and road condition (snow depth) forecasts are directly ingested from the RCTM. Second, treatments are calculated for each hour of the forecast period and the generic storm type is replaced with a specific forecast of weather and road conditions. Third, the automated determination of chemical application rate and frequency simplifies the overall treatment selection process. Finally, users may elect to disregard the automated guidance and select their own treatment schedule.

7. CHEMICAL CONCENTRATION

The chemical concentration algorithm is designed to estimate the concentration of anti-icing and de-icing chemicals as they are applied during the course of a winter storm. There are a wide variety of anti-icing chemicals available to operators. This algorithm currently supports: salt (NaCl), calcium chloride ($CaCl_2$), and magnesium chloride ($MgCl_2$). Maintenance operators choose different types and forms (dry, wet, and combinations) of anti-icing chemicals based, in part, on how well the characteristics of a particular chemical match the forecasted weather conditions.

An essential characteristic of anti-icing chemicals is their ability to reduce the freezing point of water. The phase diagram shown in Figure 6 illustrates the freezing point depression characteristics of various concentrations of salt solution (NaCl). At a solution concentration of 23.3% the freezing point of water is reduced to –6.02 degrees F. This point represents the peak freezing point depression for this chemical and is called the Eutectic Point. Solution and temperature combinations below the bounding curve on the left will result in ice formation; the curve represents the chemical's solution point. Conversely, solution and temperature combinations that fall to the right of bounding curve on the far side of the diagram will result in unabsorbed chemical. This curve is called the saturation curve. Ideally, anti-icing practices attempt to maintain the chemical concentrations between the solution point (no ice) and the saturation point (no wasted chemical).

Figure 7 illustrates the life history of anti-icing chemicals as they are applied before and during a storm. Spreader trucks (or tankers in the

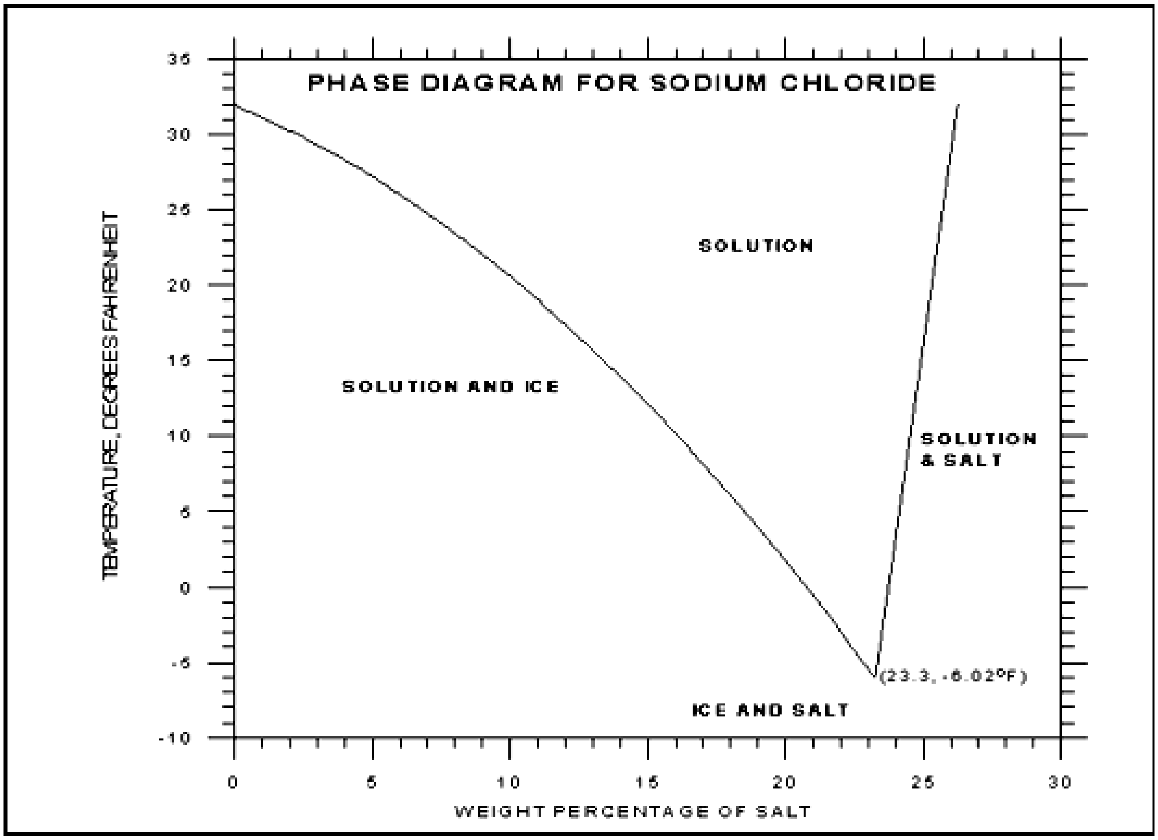

Figure 6. Phase diagram for water/sodium chloride solutions.

case of liquid chemicals) are used to spread the selected anti-icing chemical. As the truck delivers the chemical, the force of the compound hitting the road causes some of the chemical to fall off the road (road splatter). Additionally, winds may blow the chemical off the pavement before it has had a chance to stick to the road. Once the chemical is applied, routine road traffic may also scatter the chemical off the roadway (traffic splatter).

As precipitation begins to occur, the chemical mixes with the available surface water to form a chemical solution. Some of the solution is lost as the liquid drains from the roadway. The strength of this solution is directly calculated from the amount of chemicals dropped and the precipitation that falls on the road surface. The anti-icing and de-icing effectiveness of the solution is determined by knowing the concentration of the solution and the temperature of the solution (pavement temperature).

As more precipitation falls the chemical concentration continues to decrease. In addition, even without additional precipitation, the solution will slowly evaporate from or drain off the road surface. Eventually, the chemical concentration drops to a level that is insufficient to prevent ice/snow build-up (below the solution point in the phase diagram).

The concentration algorithm has been designed to capture the essential elements of the chemical application/dilution process. Many of the coefficients for the dilution process are not well understood. The amount of water runoff from the road, the evaporation rate of the salt solution, the percent loss of the dropped chemical have all been parameterized in the algorithm. This will allow the module to easily incorporate any changes dictated by new research.

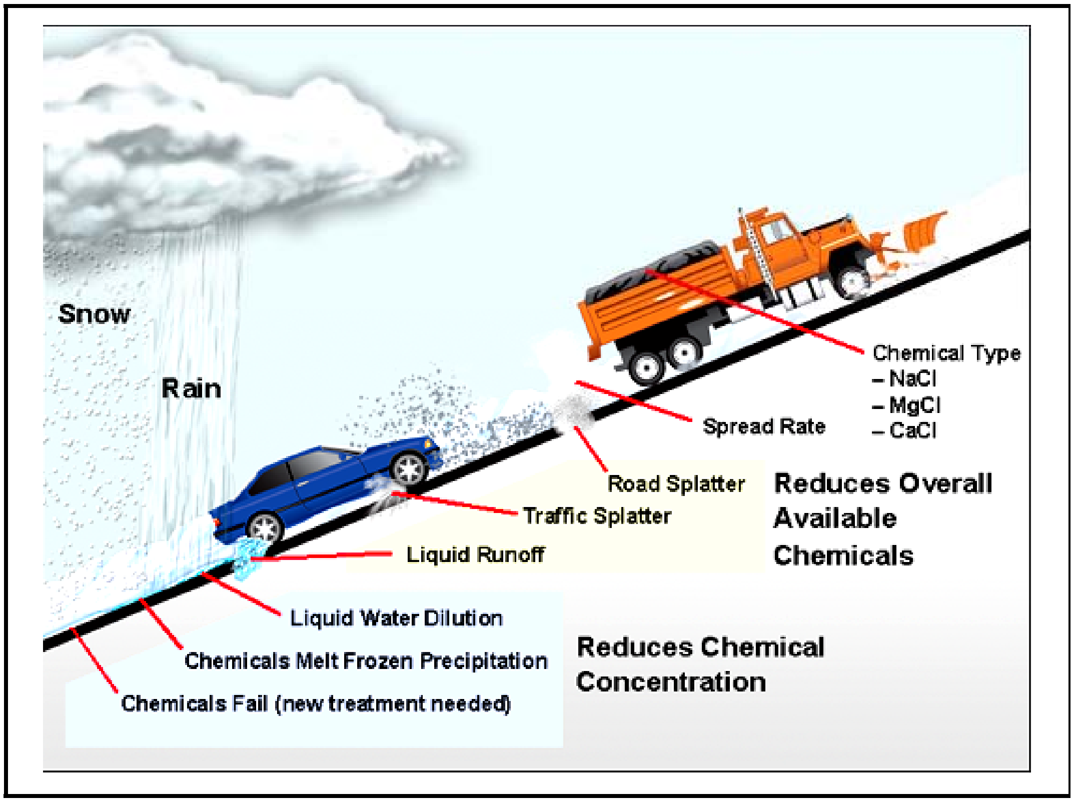

Figure 7. Overview of anti-icing (de-icing) chemical application and dilution process.

8. SUMMARY & FUTURE WORK

The work done to develop a prototype MDSS system has largely focused on integrating all the necessary algorithms together in one environment. The RCTM is a key component because it allows the system to monitor and forecast the road conditions and make treatment recommendations when conditions are below acceptable limits.

The pavement temperature module introduces SNTHERM as a potentially useful predictor of road temperatures. In addition, the chemical concentration algorithm provides a framework for further research into the expected behavior of chemicals on the road. The snow depth modeling, while distributed among other components, supplies a basic measure of the snow conditions. The concept of net road mobility, while only in the design stages, could provide a standard level-of-service metric for maintenance operators. Finally, the Rules of Practice module captures the existing FHWA guidelines, but allows individual user flexibility in applying the rules under real weather conditions.

Each of these modules captures core system capabilities, but there are many opportunities for improvement. For example, the chemical concentration algorithm could be used to determine the optimal chemical application rate instead of relying on “standard” FHWA guidelines. Additionally, the net mobility index could be used to trigger treatment evaluation. There are many more examples, and the MDSS prototype provides an environment that will allow users/researchers to examine new ways of addressing the needs of winter maintenance operators. In support of these efforts, the FHWA will be funding a test-bed experiment during the winter of 2002-03. Details of the test-bed are still being decided, but they will involve deploying the MDSS on several well-supported routes of a selected state DOT.

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