The development and validation of a snow/icepack pavement temperature thermodynamic model
by Jeffrey Ryan Bristow

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering
Montana State University

Abstract:
A model was developed to predict the temperature and melting of snow and ice on roads for a single grid point with hopes to link the model with the Radiation Thermal Road Temperature Model (RadThermRT) and perform similar calculations over a large surface with many grid points. The model's geometry consists of two separate parts, the subgrade and the ice/snowpack. Sand, unbound rock aggregate, and bituminous asphalt are three materials used to represent a typical asphalt highway cross-section. At 1 meter down in the sub-grade a diurnal depth temperature is reached, which serves as the lower boundary condition for the model. The ice/snowpack is created using multiple 1 mm thick layers with specified properties such as, density (kg/m3), impurity content (ppm), and grain size (mm). Air temperature (C), barometric pressure (mbar), relative humidity (%), incoming solar radiation (W/m2), and cloud cover (%) are the meteorological inputs used to run the model. Each ice/snow layer has an albedo, which is calculated using the Computation Albedo Routine (CAR). Conduction, convection, short-wave radiation, long-wave radiation, and the latent heat of evaporation are heat transfer methods used to change the temperature or the phase of the ice and snow layers. In addition to temperature change and phase change a runoff function predicts how much time is needed for a melted layer of snow or ice to run off. Thermal energy balance is used to derive the differential equation solved in the model. The model is solved numerically using a variation of the Crank-Nicolson method to account for unequal mesh sizes. Absorbed solar radiation and impurity content play a large role in how much and where melt is going to occur in the snow and ice layers. An experiment was run to validate the model. Pure ice was modeled on a highway test box, providing assurance that the model was working correctly. Eight hypothetical experiments are also introduced to demonstrate the model's ability to account for snow versus ice and impurity content.

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APPROVAL

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Jeffrey Ryan Bristow

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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NOMENCLATURE

A Area (m^2).

A_{imp} Amount of impurities (ppm).

AGW Aggregate weight (g).

B_x Body force (m/s^2).

cc Cloud cover fraction (%).

C_p Specific heat (J/kg-K).

ds Amount of melt (mm).

dy Thickness of a snow/ice layer (mm).

D_{oyr} Day of the year.

e_a Air water vapor pressure (kPa).

e_s Surface water vapor pressure (kPa).

ED Effective depth (m).

h_l Enthalpy of liquid water at 0° C (kJ/kg).

h_s Enthalpy of solid water at 0° C (kJ/kg).

g Gravitation acceleration (m/s^2).

I Available short-wave radiation (W/m^2).

I_a Absorbed short-wave radiation flux (W/m^2).

I_o Initial short-wave radiation flux (W/m^2).

I_r Reflective short-wave radiation flux (W/m^2).

I_t Transmitted short-wave radiation flux (W/m^2).

I_{tot_a} Total absorbed short-wave radiation flux (W/m^2).

k Thermal conductivity (W/m-K).

k Absorption coefficient (1/m).

$K_{h,e}$ Dimensionless turbulent heat transfer coefficient.

L_e Latent heat of water vaporization (kJ/kg).

L_f Latent heat of fusion (kJ/kg).

m_{im} Imaginary complex refractive index.

n Top layer of snow/ice.

P_{atm} Atmospheric pressure (mbar).

$q_{con(y)}$ Heat conduction into a layer in the y direction (W/m^2).

q_l Heat source flux associate with latent heat (W/m^2).

q_s Heat source flux associate with turbulent and radiation fluxes (W/m^2).

q_y Steady state conduction in the y direction (W/m^2).

$Q_{con(y)}$ Net conduction energy in the y direction (J).

Q_e Latent heat flux (W/m^2).

Q_g Energy generation (J).

Q_h Convection heat flux (W/m^2).

Q_l Energy generated due to latent heat (J).

Q_{lw} Long-wave radiation flux (W/m^2).

Q_s Energy generated due to heat source terms (J).

Q_{sw} Short-wave radiation flux (W/m^2).

R Gas constant (kJ/kg-K).

RH Relative humidity (%).

s Entropy (kJ/kg-K).

t_{runoff} Time for runoff (s).

T_{air} Air temperature (°C).

T_g Diurnal depth temperature (°C).

T_s Surface temperature (°C).

T_{top} Temperature of the top layer (°C).

TW Total weight (g).

u Velocity in the x direction (m/s).

U Internal energy (kJ/kg).

U_c Velocity for a confined flow (m/s).

U_f Velocity for a falling film flow (m/s).

v Velocity in the y direction (m/s).

V_w Wind velocity (m/s).

w Velocity in the z direction (m/s).

W Mechanical work (J).

x,y,z Cartesian coordinates.

α Albedo.

α_{total} Albedo.

β Attenuation coefficient (1/m).

ΔE Change in energy during phase change (W/m^2).

ΔE_s Change in energy stored (J).

Δy	Thickness of the unconfined layer (mm).
ε_s	Emisivity of snow.
λ	Wavelength (m).
μ	Viscosity of water (Ns/m^2).
τ_{ij}	Momentum flux on the i-face in the j-direction (kg/m-s).
θ	Slope of the road (^{o}).
ν	Specific volume (m^3/kg).
Φ_{ij}	Rate of momentum flux on the i-face in the j-direction (kg/s).
ρ	Density (kg/m^3).
σ	Stefen-Boltzmann constant (W/m^2-K^4).

ABSTRACT

A model was developed to predict the temperature and melting of snow and ice on roads for a single grid point with hopes to link the model with the Radiation Thermal Road Temperature Model (RadThermRT) and perform similar calculations over a large surface with many grid points. The model's geometry consists of two separate parts, the sub-grade and the ice/snowpack. Sand, unbound rock aggregate, and bituminous asphalt are three materials used to represent a typical asphalt highway cross-section. At 1 meter down in the sub-grade a diurnal depth temperature is reached, which serves as the lower boundary condition for the model. The ice/snowpack is created using multiple 1 mm thick layers with specified properties such as, density (kg/m^3), impurity content (ppm), and grain size (mm). Air temperature (C), barometric pressure (mbar), relative humidity (%), incoming solar radiation (W/m^2), and cloud cover (%) are the meteorological inputs used to run the model. Each ice/snow layer has an albedo, which is calculated using the Computation Albedo Routine (CAR). Conduction, convection, short-wave radiation, long-wave radiation, and the latent heat of evaporation are heat transfer methods used to change the temperature or the phase of the ice and snow layers. In addition to temperature change and phase change a runoff function predicts how much time is needed for a melted layer of snow or ice to run off. Thermal energy balance is used to derive the differential equation solved in the model. The model is solved numerically using a variation of the Crank-Nicolson method to account for unequal mesh sizes. Absorbed solar radiation and impurity content play a large role in how much and where melt is going to occur in the snow and ice layers. An experiment was run to validate the model. Pure ice was modeled on a highway test box, providing assurance that the model was working correctly. Eight hypothetical experiments are also introduced to demonstrate the model's ability to account for snow versus ice and impurity content.

CHAPTER 1

INTRODUCTION

During the winter months the northern United States and many other countries throughout the world suffer frequent snowfall and icy roads. This extreme weather leads to dangerous traveling conditions [Shao 1998]. As the United States and the rest of the world become more populated, the need for safer transportation will be even more of an issue than in the past. New proactive technologies that are being used today are anti-icing, roadway weather information systems (RWIS), thermal mapping, and the use of new and more sophisticated weather prediction models [Nixon 2001]. Accurate numerical prediction of road surface temperature has been proven to help save money and reduce accidents and is accepted as a viable method in the industry. These numerical predictions have demonstrated in dropping the cost of winter road maintenance [Shao and Lister 1996].

In Wisconsin the use of a winter weather system that includes a remote automatic roadside weather station and a numerical road ice prediction model has reduced the salt usage by 2500 tons and saved $75,500 during a single winter storm [Stephenson 1988]. A survey commissioned by the UK Meteorological Office shows that approximately $272M and 25-50 lives have been saved every year with the road ice prediction system in the UK [Thornes 1994]. These numbers will increase with more accurate meteorological and numerical road ice prediction models.

With the ability to predict when and where melting is going to occur, winter maintenance agencies will be able to more effectively and efficiently keep roads snow and ice free, allowing motorists, commercial services, and emergency vehicles to get to their destination faster and safer. Road ice prediction models can also help reduce excessive abrasive and chemical application, which leads to pollution of our environment [Nixon 2001].

A model for road snow/ice/water phase transformation will be developed, explained, and validated throughout this thesis. This model can prove to be very useful in a winter operation-forecasting environment. Models for balance of energy and mass are comparable to those developed by Ishikawa et al. [1999], Sass [1992], and Shao and Lister [1996]. The model is similar to other models in that it uses an energy balance taking into account sensible, radiative, latent heat fluxes, and ground conduction. The model extends the analysis by accounting for melting and runoff, also including an in depth look at how short-wave (solar) radiation is absorbed and is reflected in the snow/icepack.

Narsue et al. [1987] found absorbed short-wave radiation to be the dominant controlling factor of the ablation process and the change in snow properties. Monitoring of solar radiation and albedo was recommended for predicting ablation processes on the road. Albedo is the ratio of reflected radiation to the incident radiation [Gray and Male 1981, Marshall 1989, Wiscombe and Warren 1980a]. Although albedo will be explained, for a more detailed understanding of albedo and the optical properties of snow refer to Beddoe [2001], Marshall [1989], and Wiscombe and Warren [1980a and 1980b].

As albedo decreases, the snowpack absorbs a larger percentage of solar radiation. The more solar radiation that is absorbed provides, the greater the potential for increasing the temperature and inducing melting of the snow and ice. Impurities in the snow and ice such as carbon soot, continental dust, and volcanic ash decrease the snow's albedo, in turn increasing the amount of short-wave radiation that is absorbed [Choudhury 1981, Warren 1984, Wiscombie and Warren 1980b]. When albedo is decreased due to the addition of contaminates, an increase in absorbed solar radiation is expected. Because carbon soot is highly absorptive, about five to eight orders of magnitude greater then pure ice [Choudhury 1981], small amounts of soot will greatly increase the amount of solar radiation absorbed by the snowpack. Impurity content and distribution is very important in the model when trying to predict where melt is going to occur.

This model is one part of what will eventually be a three-part system used to model the thermodynamic properties of ice and snow on highways. The other two models are the Radiation Thermal Road Temperature Model (RadThermRT) and the computational albedo routine. At this time, input files are created to simulate RadthermRT's output and RadthermRT will eventually be linked with this model. Although RadThermRT and the computational albedo routine provide the major inputs into this model they will not be developed and only touched on briefly, for more literature on RadThermRT or the computational albedo routine see ThermoAnalytics [2000], and Beddoe [2001].

The model presented is a one-dimensional model with a lower boundary at a diurnal depth (i.e. a depth where fluctuations in temperature throughout a given day are approximately constant), taken as one meter in this analysis, continuing up through the pavement to the snow/ice air interface. A version of the basic energy equation with heat sources (e.g. radiation, sensible, and latent heat) constitutes the underlying differential equation for this model. The model is broken into numerous unequal sized layers and solved using a variation of the Crank-Nicolson finite difference method (see chapter 3) [Gerald and Wheatly 1994, Ozisik 1993].

Inputs into the model were designed to be fairly simple so a forecaster and weather forecasting model combination could be used. There are two types of inputs: one is meteorological and the second includes snow parameters. The meteorological inputs are day of the year, cloud cover, air temperature, solar radiation, barometric pressure, relative humidity, long-wave radiation, and wind speed. These inputs are outputs provided by RWIS stations in the USA [Nixon 2001]. The snow parameters are the number of 1 mm layers, layer density, impurity content, initial surface temperature, and the albedo of each layer. The albedo of each layer comes directly from the computational albedo routine.

The theoretical mathematical model was experimentally validated. The validation experiment proved to be successful in providing temperature profiles similar to the profiles created by the model. It also provided the author with a better understanding of the problem being solved. Chapters 3, 4, and 5 address the validation experiment.

CHAPTER 2

BACKGROUND

The Greater Yellowstone Regional Traveler and Weather Information System (GYRTWIS), a project taken on by the Western Transportation Institute (WTI) and Montana State University, provided the necessary support for this research. The GYRTWIS project was created to help improve weather measurements, forecasts, and dissemination of such information in the Greater Yellowstone region. The scenic beauty, abundant wildlife and intriguing natural history draws over three million people to annually visit the Greater Yellowstone region (Figure 1). The mountainous terrain and highly variable winter weather conditions make traveling in the Greater Yellowstone region potentially dangerous. Fatality statistics from 1999 show that 20% of the fatalities that occur in the Greater Yellowstone region happened because of either adverse weather or adverse road conditions (Table 1) [NHTSA 2000]. A part of the GYRTWIS project includes the development of a pavement thermal model. The research presented here is intended to be incorporated into the pavement thermal model.

Thermodynamics and Transport Phenomena

The principles of Thermodynamics are based on the observations of physical phenomena [Black and Hartley 1996]. Thermodynamics is the study of energy and its relationship with the properties of matter. Black and Hartley [1996] simply define energy as the capacity to produce change. In the present study, changes in temperature, phase, and/or the movement of fluid are of primary interest. Concepts of heat transfer, mass transfer, fluid dynamics, and how they influence the melting and freezing of snow and ice on pavement are discussed in detail in the following sections.

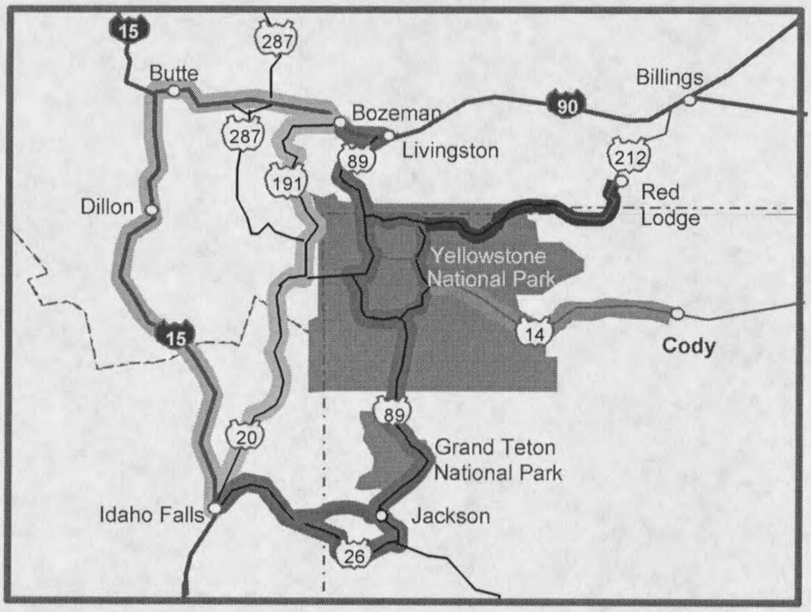

Figure 1. Greater Yellowstone Corridor.

Table 1. 1999 fatalies in Wyoming, Idaho, and Montana (reproduced from table 1 p. 2 Ballard 2001).

Road Condition / Atmospheric Condition	Dry	Wet	Snow or Slush	Ice	Sand, Dirt, Oil	Other	Unknown	**Total**
No Adverse Atmospheric Conditions	543	17	7	35	2	6	2	**612**
Rain	1	24	0	3	0	0	0	**28**
Sleet(Hail)	0	1	2	0	0	0	0	**3**
Snow	0	6	9	16	0	0	0	**31**
Fog	1	2	0	0	0	0	0	**3**
Other(Smog, Smoke, Blowing Sand or Dust)	6	0	0	1	0	0	1	**8**
Unknown	1	0	0	0	0	1	0	**2**
Total	**552**	**50**	**18**	**55**	**2**	**7**	**3**	**687**

Heat Transfer

Heat transfer can be defined as: methods that energy can be transferred by interactions of a system with its surroundings [Incropera and DeWitt 1996]. The important methods of heat transfer for the model are conduction, long-wave radiation, short-wave radiation, sensible, and latent heat of phase change.

Conduction. The definition of conduction is an exchange of energy by direct interaction between molecules of a substance containing a temperature difference [White 1991]. When energy is transferred by conduction it will occur in the direction of decreasing temperature. In winter, the temperature in the sub-grade typically decreases from the diurnal depth to the pavement surface, providing the surface with energy that will increase the temperature or change the phase of the snow and ice. In some instances the sub-grade temperatures can be lower than the snow or ice, causing conductive heat flow in the other direction, cooling the snow or ice at the surface.

Radiation. Radiation is a transfer of energy in the form of electromagnetic waves. For this study the electromagnetic waves are emitted and absorbed at the pavement surface, in the snow/icepack, and at the snow/ice surface. Radiation in this study is broken into two parts, short-wave and long-wave. Thermal pavement model is concerned with both types of radiant energy.

Long-wave Radiation. Long-wave radiation is emitted by the earth and atmosphere and has wavelengths of 4000 to 100000 nm [Gray and Male 1981]. According to the law of Stefan and Boltzman any body with a temperature greater then 0 K emits radiation. Incoming long-wave radiation is radiation that is emitted by the atmosphere. The greenhouse of the earth (e.g. water vapor, carbon dioxide, and ozone) is the main emitter of incoming long-wave radiation [Pluss 1997]. Long-wave radiation is driven by the temperature difference between the atmosphere and the earth's surface. On clear days the atmosphere is much cooler then the earth's surface, therefore pulling energy from the surface. This extraction of energy plays a major role in cooling the ice/snow surface. On occasion, clouds can be warmer than the surface, causing an inversion, and that can instead actually supplies the earth's surface with energy via long-wave radiation.

Short-wave Radiation. The radiant energy from the sun is the primary source of energy forcing atmospheric motion and many different processes in the atmosphere, in the oceans and at the earth's surface [Pluss 1997]. Short-wave (solar) radiation emitted by the sun in wavelengths of 200 to 4000 nm accounts for more than 99% of the energy received from the sun at the top of the atmosphere. Short-wave radiation can yet be broken down into three more general categories depending on wavelength; 200-400 nm ultraviolet, 400-750 nm visible, and 750-4000 nm near infrared [Pluss 1997]. Less than 0.1% of the total short-wave radiation that arrives at the earth's surface is below 300 nm due to absorption by stratospheric ozone [Marshall 1989]. Leaving visible and near infrared radiation as the biggest contributors to the heating and melting of ice and snow. Small amounts of impurities (e.g. carbon soot, volcanic ash, dust, etc.) in pure snow/ice can drastically change how solar radiation is absorbed or reflected. According to Wiscombie and Warren [1980b] concentrations of 1 part per million by weight (ppmw) can lower snow albedo by 5-15% from high values of 96-99%. As mentioned earlier, lowering the albedo allows more solar radiation to be transmitted or absorbed in the snowpack.

Turbulent Fluxes. The latent heat of evaporation, sublimation, and condensation is the internal energy associated with the phase change of the system [Cengel and Boles 1994]. When compared to radiation, the convective flux and the latent heat flux are often relatively small but still play a role in cooling or warming the snow surface. Convection, sometimes known as sensible heat, is the exchange of energy between a solid (ice/snow) and an adjacent liquid or gas (air) which is in motion [Cengel and Boles 1994]. This process is affected by wind speed and air temperature.

Mass Transfer.

Water is the only substance that occurs naturally on earth in all three phases (e.g. solid, liquid, and vapor) [Hudson and Nelson 1990]. Phase change is a process where by the physical characteristics of the substance are altered without a change in temperature. When dealing with snow/ice on the highways all three phases of water are present. For water, the phase change temperature from solid to liquid is 0° C and for changing from liquid to vapor the temperature is 100° C at standard pressure. A simple example of phase change is a block of ice at a temperature below its freezing point (0° C). When heat is added the block will increase in temperature until the surface of the block has reached its melting point. At this stage the block will still be absorbing energy but not changing temperature, all the energy is going into changing the phase of the block. After