A spectrually integrated temporal albedo model for thin composite layers of snow and ice on roads
by Andrew Gregory Beddoe

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering
Montana State University
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Abstract:
This study presents a spectrally integrated solar albedo model for thin composite layers of snow, ice and water on roads. The model is intended to support micro-scale thermal mapping models for forecasting highway pavement temperatures and surface conditions.

The snow-on-slab albedo (SOSA) model estimates the temporal road albedo by modeling surface conditions on highways that strongly affect solar albedo. Snow grain size, impurity concentration and optical mass were found to be important factors. These three factors were highly influenced by traffic and winter maintenance operations.

SOSA is composed of two components (1) a computation albedo routine CAR and (2) a pavement snow conditions routine SCR. CAR calculates visible, near infrared and solar albedos (0.3 - 5 /µm) from 7 physically based parameters: snow grain radius (&,mu;m), carbon soot concentration (mass fraction), mass cross-section (g/cm2), zenith cosine, atmospheric pressure (millibar), underlying surface albedo, diffuse fraction, surface downflux and atmospheric transmittance. SCR models the optical mass of water, ice, snow and sand, light absorbing impurities and the optical grain size. Inputs to SCR are meteorological parameters, surface energy fluxes and traffic parameters.

The optically equivalent grain size required in the model was 1/10th the observed grain size, partially due to the measurement protocol, which classified parficle size by the longest dimension. Optical radii ranged from 50- 150 µm. The sanding materials were the principle light absorbing impurity. Carbon residue from vehicle exhaust and tire residue was insignificant. The sanding material was composed primarily of basalt and granite and had ~0.07% the optical influence of carbon soot in the model. The 0.07% normalization factor is related to the ratio of the imaginary indices of refraction between carbon soot and the bulk sanding material.

Despite erratic and quickly changing surface conditions, SOSA proved effective in calculating albedo. SOSA had an overall standard deviation of 0.15 from observed albedos for the entire road and shoulder. The accuracy of the model improved when it was restricted to calculate albedos inside the lanes only. The standard deviation decreased to 0.11. As a result SOSA estimated surface temperatures accurately over a 24hr period. Surface temperature standard deviations were less than 1.7°C from measured values.

# A SPECTRUALLY INTEGRATED TEMPORAL ALBEDO MODEL FOR THIN COMPOSITE LAYERS OF SNOW AND ICE ON ROADS

by

Andrew Gregory Beddoe

A thesis submitted in partial fulfillment
of the requirements for the degree

of

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Of a thesis submitted by

Andrew Gregory Beddoe

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

The following are the symbols used in the thesis

| | |
|---|---|
| A | Cross-sectional control area ($m^2$). |
| AHP | Average hourly pass rate of winter maintenance vehicles. |
| AHT | Average vehicles per hour. |
| APT | Average vehicles per 15 minutes. |
| B | Thermal quality or fraction of ice in a unit mass of wet snow. |
| $C_p$ | Specific heat (J/kg-K). |
| $d_f$ | Diffuse fraction of solar downflux. Subscript c refers to clear sky diffuse fraction. |
| $d_s$ | Geometrical snow depth (m). |
| $D_{oyr}$ | Day of the year. |
| E | Amount of erosion. Subscripts v and m refer to vehicles and winter maintenance, respectively ($kg/m^2$). |
| $e_{a,s}$ | Water vapor pressure (kPa). Subscripts a and s refer to air and surface, respectively. |
| $f_{3-3}$ | Fraction of near infrared flux from 3 to 5 $\mu$m. |
| $f_{basalt}$ | Fraction of basalt in sanding materials. |
| G | Global irradiance ($W/m^2$). Sum of diffuse and direct solar radiation. |
| g | Gravitational acceleration ($m/s^2$). |
| $G_{xs}$ | Geometrical cross-section ($m^2$). |
| I | Radiation flux ($W/m^2$). Subscript o stands for incident flux. |
| k | Boltzman molecular gas constant (J/molecule-K). Equation (42) |
| k | Thermal conductivity (W/m-K). |

$k_e$ Extinction coefficient ($m^{-1}$). Subscripts a and s stand for absorption and scattering, respectively.

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

L Latent heat of transformation (kJ/kg). Subscripts f, s and v refer to fusion, sublimation and vaporization, respectively.

L Longwave radiation flux ($W/m^2$). Subscripts i and o refer to incident and emitted IR, respectively.

M Amount of melting in snow layer ($kg/m^2$).

m Mass (kg).

$m_{mol}$ Molar mass of air (kg/mol). Equation (42).

$m_{re, im}$ Complex refractive index. Subscripts re and im stand for real and imaginary parts, respectively.

$m_{xs}$ Optical mass cross-section ($kg/m^2$).

n Cloud cover fraction.

N Number density ($m^{-3}$).

n Number of particles. Equation (11).

$N_a$ Avagodro's number (molecules/kmol).

$N_f$ Normalization factor.

P Amount of precipitation ($kg/m^2$).

p Pressure (kPa or mmbar).

$P_i$ Precipitation intensity (m/s).

Q Energy flux ($W/m^2$).

R Gas constant (kJ/kg-K).

r Particle radius ($\mu$m).

$R_{DAPT}$ Average diurnal vehicle flow rate (Vehicles / 15 minutes).

$R_{ef}$ Spectral reflectivity.

$Re_x$ Dimensionless Reynolds number.

S Equivalent soot concentration of contaminate (mass-fraction).

t Atmospheric transmittance.

$\Delta t$ time increment (seconds).

T Temperature (° C).

U Wind speed (m/s).

v Velocity (m/s)

V Volume ($m^3$).

WS Wavelength separation between visible and near infrared regions (0.7 or 0.9 $\mu$m).

x Optical path length or relative air mass (m).

x,y,z Cartesian coordinates.

$x_c$ Characteristic length (m).

$x_p$ Characteristic size of scattering particle used in Mie Theory.

y Elevation above reference pressure (m).

$Z_e$ Extinction efficiency. Subscripts a and s stand for absorption and scattering, respectively.

$z_g$ Nodal distance (m).

$\alpha$ Albedo.

$\beta$ Attenuation coefficient ($m^{-1}$)

$\epsilon$ Surface emisivity.

$\epsilon$ Internal energy per unit mass (J/kg). Equation (71).

$\theta$ Zenith angle (°).

$\Lambda$ Thermal diffusivity ($m^2/s$).

$\lambda$ Wavelength (m).

$\mu_0$ Cosine of the zenith angle.

$\nu$ kinematic viscosity ($m^2/s$). Equation (68).

$\nu$ Specific volume ($m^3/kg$). Equations (60) and (61).

$\rho$ Density ($kg/m^3$).

$\sigma$ Stefen_Boltzmann constant ($W/m^2\text{-}K^4$).

$\sigma_e$ Extinction cross-section ($m^2$). Subscripts a and s stand for absorption and scattering, respectively.

$\tau_o$ Optical snow depth.

$\phi$ Relative humidity.

# ABSTRACT

This study presents a spectrally integrated solar albedo model for thin composite layers of snow, ice and water on roads. The model is intended to support micro-scale thermal mapping models for forecasting highway pavement temperatures and surface conditions.

The snow-on-slab albedo (SOSA) model estimates the temporal road albedo by modeling surface conditions on highways that strongly affect solar albedo. Snow grain size, impurity concentration and optical mass were found to be important factors. These three factors were highly influenced by traffic and winter maintenance operations.

SOSA is composed of two components (1) a computation albedo routine CAR and (2) a pavement snow conditions routine SCR. CAR calculates visible, near infrared and solar albedos (0.3 – 5 $\mu$m) from 7 physically based parameters: snow grain radius ($\mu$m), carbon soot concentration (mass fraction), mass cross-section (g/cm$^2$), zenith cosine, atmospheric pressure (millibar), underlying surface albedo, diffuse fraction, surface downflux and atmospheric transmittance. SCR models the optical mass of water, ice, snow and sand, light absorbing impurities and the optical grain size. Inputs to SCR are meteorological parameters, surface energy fluxes and traffic parameters.

The optically equivalent grain size required in the model was 1/10$^{th}$ the observed grain size, partially due to the measurement protocol, which classified particle size by the longest dimension. Optical radii ranged from 50 – 150 $\mu$m. The sanding materials were the principle light absorbing impurity. Carbon residue from vehicle exhaust and tire residue was insignificant. The sanding material was composed primarily of basalt and granite and had ~0.07% the optical influence of carbon soot in the model. The 0.07% normalization factor is related to the ratio of the imaginary indices of refraction between carbon soot and the bulk sanding material.

Despite erratic and quickly changing surface conditions, SOSA proved effective in calculating albedo. SOSA had an overall standard deviation of 0.15 from observed albedos for the entire road and shoulder. The accuracy of the model improved when it was restricted to calculate albedos inside the lanes only. The standard deviation decreased to 0.11. As a result SOSA estimated surface temperatures accurately over a 24hr period. Surface temperature standard deviations were less than 1.7°C from measured values.

# CHAPTER 1

## INTRODUCTION

Winter driving conditions are hazardous and often confront motorists with extreme temporal and spatial variability because of local topography, traffic, maintenance practices and meteorological influences. Winter conditions also contribute a large economic burden in loss of property, time delays, and labor and material costs expended in winter maintenance operations [Hanbali 1992]. Many roads may see the highest injuries and fatalities during snowy and icy conditions in part due to the high variability of snow and ice on roads, which complicate anti-snow and ice measures [Naruse et al. 1987]. Knowing exactly when and where snow and/or ice will begin to melt or refreeze could improve planning, help cut costs of snow and ice control and reduce hazards for winter maintenance crews and road users. Because of this, motorists and traffic management personal are in continual need of accurate real-time and forecasted road and weather conditions along rural roads and highways.

To assist in these efforts a more sophisticated snow albedo (reflectivity) model, controlled by the physical properties of snow, is needed for weather-related micro-forecast pavement temperature and condition models. A physically based albedo model will broaden the physical understanding and forecast accuracy of snow and ice formation and ablation on roads thus improving the effectiveness and deployment of anti-snow and ice measures. Albedo $\alpha$ plays a critical role in modeling efforts because it provides a quantitative measure of the fraction of incident solar radiation absorbed (e.g. fraction

absorbed = 1 – $\alpha$) near the surface, and is the dominate energy available to cause increases in road surface temperatures and melt snow on roads during winter [Ishikawa et al. 1987, Naruse et al. 1988, Nakawa et al. 1992].

Albedo refers to the reflectivity of a surface (fraction of energy reflected) in the solar spectrum (generally between 0.2 to 5 $\mu$m). and is commonly parameterized as the spectrally-averaged (allwave) albedo. The word itself, albedo, in late latin means whiteness, from the latin albus (white).

Snow is an excellent reflector of shortwave (solar) radiation and emitter of longwave radiation. This means that snow usually lowers absorbed solar energy during the day while effectively emitting longwave radiation at night, creating a net radiation loss from a surface. These conditions commonly cause surface cooling which can lead to ice formation on the road surface.

The albedo of a snow covered road is the result of a composite structure of pavement, ice, anti-skid materials (sand aggregate) and snow acting in concert to absorb, scatter and reflect incident radiation. Of these, snow has the greatest influence on the observed albedo because of its high albedo (e.g. pure semi-infinite snow 0.7 to 0.85, [Marshall 1989]) as compared to dry asphalt (e.g. new asphalt has an albedo of 0.04 and aged asphalt ~5 to 10 years has a mean albedo of 0.12 $\pm$ 0.03, [Pomerantz et al 1999]), water ( e.g. an albedo of 0.06 for solar heights > 40 degrees, Fig 7.5, [Kondratyev 1969]) and common anti-skid abrasives (e.g. albedo of gray sand 0.18 to 0.23 , Table 7.3, [Kondratyev 1969]) used in winter maintenance.

It is apparent, then, that snow albedo has a enormous potential to change the amount of solar energy absorbed at the surface of the road. A change in snow albedo from 0.8 to 0.4 (e.g. from removal of snow by plowing or addition of light absorbing contaminates such as anti-skid materials) triples the amount of solar energy absorbed on the surface from 20% to 60% and may greatly accelerate melt [Naruse et al. 1988]. Even slight fluctuations in snow albedo may alter the onset of snowmelt or refreeze on the road, as indicated by Warren [1984] and Brown [1982] for undisturbed snow covers. Thus, an accurate knowledge of the surface albedo is required to precisely model when snowmelt and refreeze might occur.

Snow melting or aging generally has a positive feedback on the snow albedo. Albedo naturally decreases as snow ages because of snow grain growth and a decrease in snowcover thickness [Warren 1984]. As the albedo drops the snow cover is more efficient at absorbing solar energy which in turn increases ablation. This cycle is accelerated when traffic and winter maintenance are introduced and can rapidly change the snowcover conditions, which translates to a rapidly changing albedo [Ishikawa et al. 1987, Naruse et al. 1988]. Combined with dynamic solar effects from shadowing and thermal energy exchange between surfaces, particularly in mountainous regions, pavement temperatures and conditions during winter can fluctuate drastically along a road within a close distance.

Most snow albedo models to date have been developed for use in global climate modeling and were concerned only with natural snow covers experiencing seasonal metamorphism and ablation. The earliest albedo parameterizations treated albedo quite

crudely, generally prescribing snow albedo as a single value, or basing it on a distribution of the surface albedo [Marshall 1989]. Others have taken a simple parameterization of snow albedo, dependent on temperature, age of snow, zenith angle or latitude [Table 1.1, Marshall 1989]. However, many of the earlier parameterizations are derived from data at a single site and are not universal parameterizations, as published by Pluss [1997]. A more sophisticated approach was applied to model snow albedo by Marshall [1989], based on the sophisticated theoretical work of Wiscombe and Warren [1980a and 1980b, here after WWI and WWII]. Marshall [1989] developed simple functions, which accurately fit the spectrally integrated (allwave) results of the theoretical spectral albedo model. The model requires 7 realistic physically tuned inputs, which allows the parameterization to be transferable to other locations. However, the model is developed for use in atmospheric general circulation models (GCMs) and seasonal snowcovers and is not directly applicable to thin snow and ice covers on pavement where direct influences from anthropogenic sources must be considered.

Traffic and winter maintenance are factors that indirectly influence snow albedo on roads, but have not been considered at all in albedo models. Actions by vehicles and maintenance practices both alter the physical snow properties, thus snow albedo. Vehicles mechanically break snow crystals, compact snow, mix contaminates, move and erode snow on the road. Maintenance operations deposit large amounts of contaminates on the snow through application of abrasives and remove snow mass by plowing. In addition, differences in local traffic and anti-snow and ice operations contribute to the variable snow conditions along the road. The net result of these transportation influences

is to increase the inhomogeneity and to accelerate metamorphism and ablation of snow roads as compared to a seasonal snowpack, which complicates measuring and modeling efforts.

Within this thesis a allwave albedo model for thin composite layers of snow and ice on pavement (snow-on-slab) is presented. The albedo routine is adapted from a physically parameterized snow albedo model [Marshall 1989]. The snow-on-slab albedo (SOSA) model includes the effects from motor traffic and winter maintenance on the physical snow structure, contamination and ablation on pavement and is intended to support road surface temperature modeling efforts for snow and ice covered roads. The allwave albedo is calculated based on realistic physical conditions of the snowcover and the pavement.

This snow-on-slab albedo model is seen as necessary to improve the accuracy of pavement temperature forecasting. It provides the first ever (to the knowledge of the author) physically-based albedo model applied to snow and ice in a transportation setting. The model was developed to be incorperated into WinThermRT to improve albedo estimates to achieve more accurate forecast of surface temperatures (see Chapter 2). Improvements in surface temperature modeling will contribute to improved safety and efficiency on rural roads. Success of the thermal modeling will assist in increasing traveler safety through reduction in accidents, improve maintenance operations through effective and timely use of resources, and demonstrate the feasibility of ITS in rural applications.

The following summarize the rational for the thesis:

1. The high variance of albedo of snow and ice on roads plays an important role in the surface energy budget.
2. Current classification of snow and ice on roads is lacking in a sophisticated approach in modeling albedo.
3. Future highway safety and efficiency will benefit from a physically – based albedo model tailored to road and highway snow.
4. Assist in development of intelligent transportation systems in rural settings.
5. Improve accuracy of strategic road weather and condition forecasting models.

# CHAPTER 2

# BACKGROUND

Support for this research was provided by the *Safe Passage* Project, a cooperative effort by the Western Transportation Institute (WTI), MSU-Bozeman and the Montana Department of Transportation (MDT). Funding was provided by the Research and Special Programs Administration of the U.S. Department of Transportation through WTI.

The *Safe Passage* Project is concerned with optimizing weather related operations, motorist safety and incident management along Interstate 90 (I-90), a major east-west corridor between Livingston and Bozeman (Figure 1). Severe weather conditions common in the northern rockies, that consistently plague the corridor during winter months, compel the project to focus on the issue of weather and weather-related pavement conditions, reported as contributing to up to 70% of the accidents between 1994-1999 [Accident statistics, MDT, Safety Management Section, 1998]. Intelligent Transportations Systems (ITS) technologies such as road and weather information systems (RWIS), employed in *Safe Passage*, provide site-specific meteorological and pavement temperature data, an important component to icing. However, it is economically impossible to line entire stretches of roads with sensors, thus requiring extrapolation between RWIS sites. This limits strictly using RWIS as decision support tools regarding appropriate action in snow and ice control efforts because of the limited accuracy of extrapolated pavement temperatures due to small amounts data between sites. As a result a micro-forecast pavement temperature model (WinThermRT) which utilizes

ITS technology in conjunction with National Weather Surface (NWS) forecast data is in continuing development.

This thesis supports development of the computational thermal model (WinThermRT), an integral component of *Safe Passage,* which is intended to accurately micro-forecast pavement temperatures and roadway conditions. The thermal model (WinThermRT) is adapted from a computational model called PRISM (Physically Reasonable Infrared Signature Model) used by the U.S. Military to model surface temperatures of vehicles for use in infrared imagery [Adams and McDowell 1991]. PRISM uses a series of flat plates to represent the three-dimensional shape of a vehicle. Shadowing and surface to surface re-radiation are accounted for within the model. The concept was expanded to terrain and highways through employment of Geographic Information Systems (GIS) and Digital Elevation Maps (DEM) [Adams, WTI Report, Vol. 4 (1), March 2000].

Currently, WinThermRT micro-forecasts pavement temperatures to a 30 m resolution (Standard United States Geological Service (USGS) Dimensions) by extrapolating meteorological forecasted data (on a 40 km grid) obtained indirectly from the National Weather Service (NWS) and Eta program (a mesoscale meterological model, for more detail contact the National Oceanic and Atmospheric Administration NOAA) via the Advanced Regional Prediction System [ARPS, Xue et al. 2000]. The albedo model was developed only as a point model within WinThermRT. The spatial extrapolation of albedo across the complex terrain grid is accomplished through WinThermRT's platform.

Therefore, the surface albedo at the grid point represents the averaged abledo for a 30 m square surface over the road.

Bozeman Hill (BZH) was chosen as the research site. It is located within the corridor at mile marker 321.1 (Figure 2). Only west bound lanes of I-90 were studied. Bozeman Hill was selected as the site because it provided the highest point along the highway within the corridor and is a good representative of the severe weather within the corridor or other mountain passes. Also, an existing MDT RWIS adjacent the highway helped reduce cost and construction time and provided an existing system into which additional radiation sensors could be integrated.

## Radiation

Thermal models for pavement icing are primarily concerned with radiant energy exchange on a surface in the shortwave and longwave regions. Albedo is important in radiant energy exchange on surfaces because knowledge of albedo makes it possible to determine the amount of heat obtained from incoming shortwave (solar) radiation.

### Shortwave Radiation

Radiation from the sun is the primary energy fueling atmospheric motions and different processes in the atmosphere, on the earth's surface and in the oceans [Kondratyev 1969, Pluss 1997]. Radiation emitted by the sun may be regarded as