The weather meets the road – A relationship with (heat) balance

The weather impacts your life on a daily basis. You experience it every time you wonder "What clothes shall I wear?" or "Shall I go jogging?" before stepping outside your home. Roads are affected by the weather, too. Whether you are driving on a stormy wet day or on a cold-freezing morning, you spend most of our time trying to guess how rain, snow, fog, wind and ice may impact the pavement underneath your car's wheels and, as a consequence, decide your next course of action – to slow down or to not overtake the truck in front of you.

According to the U.S. Department of Transportation adverse weather events such as those listed above and slippery pavement conditions due to ice, snow and slush cause together more than 1,200,000 vehicle crashes, nearly 6,000 casualties and over 445,000 injuries each year [1]. These numbers are sky-rocketing, but can be reduced.

When a national weather service issues a "road danger warning" on TV for the following day, we take care to drive more cautiously. In addition, road maintenance services get ready to keep roadways in optimum conditions and travel-safe. Forecasting *road weather*, i.e. how and when unsuitable weather conditions may influence the kilometres of asphalt and concrete on which we travel every day, is therefore fundamental to prevent weather-related accidents and guarantee our safety on roads. A *heat balance* model can be used for this purpose as it predicts the most important variable governing the dryness, wetness and iciness of a road surface – the *road surface temperature*. Road surface temperature is the temperature of the road pavement and it is influenced by numerous interacting parameters.

A pavement surface is exposed on one side to sunlight, air and traffic. Each of these affects the pavement in different ways [2, 3].

Sunlight is the light (*electromagnetic radiation*) given off by the Sun. Since the atmosphere is mainly transparent to short *visible* wavelengths, most of the sunlight is transmitted through and it reaches the road, where it is absorbed. Energy is thus transferred to the road in form of *heat*. The more sunlight a pavement receives the warmer it gets. If the road is in shadow, be it from trees, hillsides or other objects, it will not receive as much solar radiation and it will stay cooler (Figure 1).

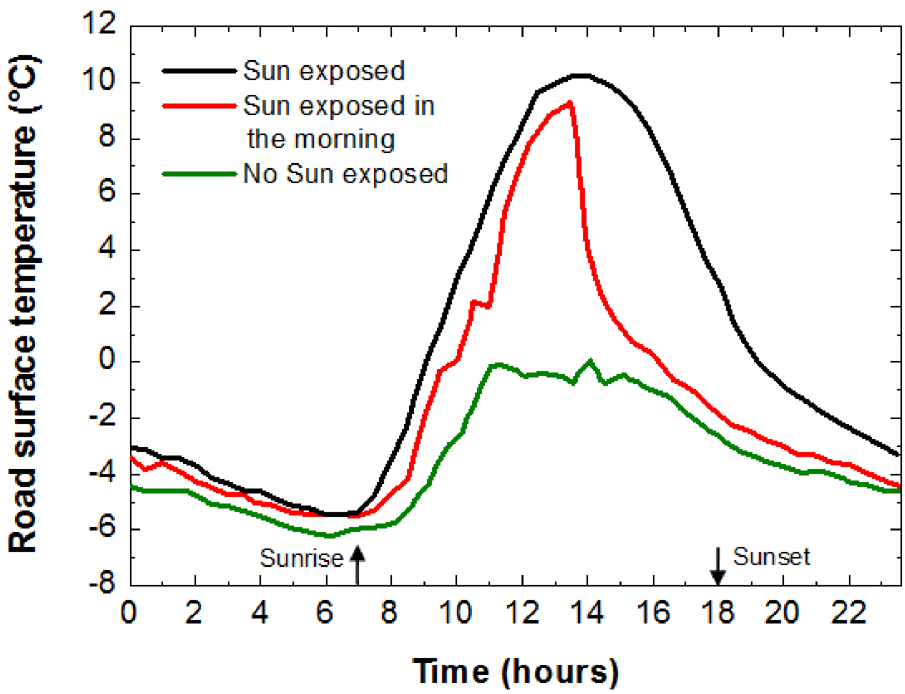

FIGURE 1 | *Screening effect on road surface temperature at three different locations: one fully exposed to sunlight (black), one exposed to sunlight in the morning and screened by a nearby forest in the afternoon (red), and one screened by a forest throughout the day (green). Roads are cooler when and where sunlight is prevented from reaching the pavement [4].*

The road does not just receive radiation, it also gives off radiation. During daytime, as heat is absorbed from incoming shortwave sunlight, heat is emitted from the pavement at long *infrared* wavelengths. At night, there is no warming from sunlight absorption and the pavement keeps on radiating heat away. On clear calm skies heat is lost to space and the road temperature decreases (*radiative cooling*), reaching the lowest value near sunrise (Figure 1). As the pavement gets colder and colder, so does the air just above it, which becomes denser and heavier than the warm, lighter air further above. A condition where air temperature increases with height is called "temperature inversion" [2]. On overcast nights the heat loss from the pavement is less. Clouds can absorb some of the heat emitted from the ground and then re-emit it back downwards, thus reducing surface cooling and keeping the road warm. Heat is then transferred into the near air by conduction as air molecules collide with those of the surface. This transfer of heat, called *sensible heat*, causes a rise in the temperature of the air. Air molecules start to move faster and to collide more frequently with each other, moving sensible heat upwards via convection throughout the atmosphere.

In addition to sensible heat, air also contains *latent heat*. Latent heat is a form of heat related to how much water vapour air can hold. Water vapour is the gas phase of water and it is invisible. It can be seen only when it changes to a liquid or solid phase, that is, when it condenses into water droplets or ice crystals. This is what happens when, for example, you put a glass lid on pan full of boiling water. You see small droplets of water forming on the inner surface as vapour rises from the very hot water and touches the cooler lid. Condensation of water vapour takes place on road surfaces, too. Let's consider again the condition of temperature inversion. As the temperature of the air closest to the pavement decreases over a calm clear night, so does the capacity of that air to hold water vapour. When the air temperature reaches a value known as *dew point temperature*, water vapour cannot be gas anymore and it must change phase. It may turn into water droplets (dew) on pavements with temperatures above freezing (0°C) or into ice crystals on pavements with temperatures below freezing. When temperatures are warmed up by sunlight the following morning, air may return above the dew point temperature. Water droplets may thus evaporate and ice crystals sublimate, allowing water to reach air again as invisible gas. Every time a phase change occurs, heat as *latent heat* is transferred at the pavement. Latent heat is released as sensible heat when water molecules condense. Sensible heat is requested and converted to latent heat when water molecules vaporize to gas.

The exchange of sensible and latent heat on the road surface occurs because heat and water vapour (*moisture*) are transported by air mixing, which can occur due to wind [2]. We have already seen that on nights with no or weak winds cold air sets down on a road pavement while this is undergoing radiative cooling. However, when the winds blow strong, warmer air is moved from aloft down to the pavement and there it is mixed with the cold bottom air, thus preventing heat loss from the road. Air mixing can be a consequence of traffic as well [5]. When moving in your car, you stir the surrounding air with the heat emitted from the engine and from the friction between the tires and the pavement. The input of heat from vehicles is also responsible for increasing road surface temperatures, with trafficked lanes up to 2°C warmer than less trafficked lanes (Figure 2).

Figure 2 | *Drying effect on a highway road. The right lane is dry because of the heat and air mixing from running vehicles. The left lane is wet because less trafficked [5].*

Looking down from the pavement

Sunlight, air and traffic affect a road on one side only, the one above the pavement. The other side, the one below the pavement, is affected by the ground underneath (*subsurface*) [2, 3]. The ground acts like a heat reservoir that slowly builds up over the summer as more heat is stored in the day than it is lost overnight, and slowly empties out over the winter as longer nights increase the amount of heat radiated away. Therefore in autumn the ground still retains a great amount of heat from the summer and, as a heater, it keeps the pavement warm. In spring the ground has lost most of its heat reservoir, it is much colder than it was in autumn and cannot warm up the pavement anymore. The *subsurface temperature* thus affects the road surface temperature and how the road surface reacts in turn to the weather above. Think of a snowfall in early winter season. You may see snow accumulating on the pavement. However, being the subsurface temperature still high, the road surface is warmed up to above freezing temperatures. Once the snowfall stops, the accumulated snow will therefore start melting. Consider now a rainfall in an early spring day. The low subsurface temperature may keep the pavement temperature below 0°C so as the rain touches the pavement, it may freeze and form a transparent layer of road ice.
However, not all roads have ground underneath. A bridge, for example, is surrounded by air from above and below. It has a wider surface area to lose heat from and it cools down more quickly than a pavement leant against a ground. Composition has also a part in this. Bridges are usually made of steel and concrete, which conduct heat very well. This means that the heat trapped within a bridge is transferred efficiently from inside to the surface, where it is lost to the air around. Conversely, roads are made of asphalt. Being a poor conductor, asphalt prevents any stored heat from leaving the pavement, which therefore will take longer to cool down.

At the pavement: Road ice as an example of road weather

Sunlight, air, traffic and soil are responsible for transferring heat to and from the road surface (Figure 3). This transfer defines the temperature of a road surface and how it changes over time.

As the air closest to the pavement cools through a calm clear night, its temperature may reach the dew point temperature. It might even be already at it if rich in moisture from recent rains, melted snow or fog. When the air dew temperature is above the road temperature and the road temperatures cools below 0°C, road ice will occur. Road icing is the formation of ice and/or frost on pavements and represents one of the most dangerous meteorological hazards faced by travellers. By reducing the pavement friction with vehicle tyres, it makes road surfaces slippery, vehicles manoeuvrability difficult and accidents more likely.

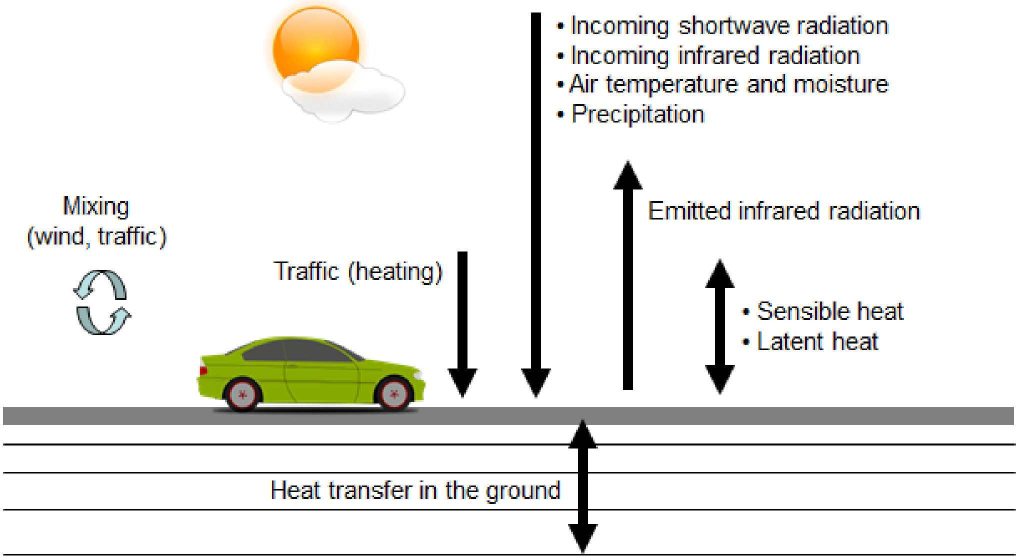

Figure 3 | *A schematic representation of the processes involved in the heat transfer to and from the road surface (adapted from [6]).*

Predicting road icing is however possible. As we have learnt, the key conditions to look for are:

- Clear night skies
- Moist air near the road surface
- Light or no winds
- Bridges
- Pavement temperature less than dew point temperature
- Pavement temperature below freezing

with the pavement temperature playing the most critical role. Its profile, i.e. how the pavement temperature changes overtime in response to all the influencers just discussed, can be forecast beforehand through a *road weather model.* A road weather model is an *energy balance* model, i.e. it simulates the heat (*energy*) transfer at the road surface by finding the one and only *equilibrium surface temperature* at which the heat going into the road surface is balanced by the heat coming out the road surface. To do so a road weather model first needs recent observations on meteorological parameters, such as air/dew temperature, wind speed, precipitation, road conditions and road surface/subsurface temperature, from road weather stations. These records are used to calculate how heat has been transferred from the soil to the road surface to the air above and vice versa. The model then takes weather forecasts from numerical prediction models and uses them to project heat transfer calculations from the past into the future. The final result is a profile of future equilibrium surface temperatures. This profile can be used to simulate the accumulation of precipitation on the road surface either in liquid or solid form, thus predicting the outcome of road icing [6, 7].

In conclusion, the next time you are driving remember that...

Roads are constantly affected by the weather. Whether it is dry, wet or icy, the amount of heat being transferred to and from the road surface is the key to determine the status of the road stretch you travel every day. Weather-related hazards, such as road icing, occur under conditions that are well known and can be predicted through a road weather model. A road weather model combines the past, present and future meteorological parameters affecting the pavement from above with the state of the ground underneath. Through them it calculates the road temperature that exactly balances the heat transfer at the road surface at any one moment, and it forecasts how pavement conditions are likely to change in the next hours. Incorporating a road weather model into a road warning system can help us – the drivers – and road maintenance personnel to evaluate possible threats, take action against them and guarantee our safety.

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About the Author

Claudia Di Napoli is a research meteorologist. After completing her Ph.D. in physics, she has been working on the applications of weather sciences to the road sector. She is currently investigating how weather numerical prediction models and measured road/weather parameters can be used to predict when and where ice will form on roads in the Italian Alps. A timely and accurate forecast of road ice would help winter maintenance personnel to spread de-icing substances, such as salt (sodium chloride), in a more efficient and conscious way. Salt is regularly used to melt street-clogging ice from paved roadways in winter, but it can be harmful to the surrounding environment when spread in excessive quantities. In collaboration with the weather prediction team of the EU-LIFE+ CLEAN-ROADS project, Claudia aims to use road ice forecasts as a tool for reducing oversalting and related environmental damage, while guaranteeing road safety.