Impacts of climate change on frost design and winter maintenance activities in France

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Summary

The purpose of this work is to quantify the evolution of current practices in frost design method, and in winter maintenance of roads in France for the coming century, in accordance with climate change. The work is based on climate simulations from the database of the French IMFREX project, which used the ARPEGE-CLIMAT model of Météo-France. It simulates the climate evolution during the 21st century under an A2 scenario of the IPCC (Intergovernmental Panel on Climate Change). The paper describes in a first part, the current conception and maintenance of french road structures ans in a second part the climate simulations obtained from the database of IMFREX project. Finally the impact of the decrease of winter constraints on frost design method and winter maintenance in the future are discussed.

1. French pavements in winter : current conception and maintenance

Design of winter maintenance services in France is defined on the basis of meteorological criteria. It particularly takes into account snow occurrence (since means allocated to snow allow also to cover black ice events). Two parameters are important : the snow intensity and the snow duration. They are part of the “non-overtaken” limit condition as mentionned in technical winter maintenance guides. This limit condition is the one below which road manager can reach the announced service level, with his own means (winter maintenance engine and staff). Above this limit, he has to mobilize additionnal means (sub-contractors) or reduce service level.

The frost design method [1] consists in a “checking” with respect to frost/thaw phenomena. It makes sure that the roadway designed from mechanical calculations can withstand a given winter chosen as a reference, without notable damage. The road structure is designed so that the allowed frost index IA of the pavement, evaluated according to the frost susceptibility of the subgrade, the thermal protection and mechanical function fulfilled by the roadway, is greater than the reference frost index IR. IR characterizes the severity of winter, according to the area, against which a choice of protection of the roadway would be done.
Two reference indexes are usually retained : exceptional winter frost index (the highest index since

1951) and non exceptional rigorous winter (winter with 10 years occurrence). Frost design method has a major influence on pavement design in the North East of the France, where the reference atmospheric index are important. Most structures, once the mechanical design done, have to be "over-designed" to take into account specific thermal stress.

2. The climate change in France : available database and impacts on frost design and winter maintenance

The climate simulations used here were obtained from the database of the French IMFREX project (http://medias.cnrs.fr/imfrex/). The climate model used was the third version of the ARPEGE-CLIMAT atmospheric model [2]. The model was used with a variable grid : the horizontal resolution was better over Europe than in the rest of the world, the horizontal resolution over France being around 50 km [3]. As this project was originally designed for the study of extremes events three sets of simulations were done for the current condition (1961-1999) and the future situation (2071-2099) in order to increase the probability of this kind of events. The three members of each set differ only by the atmospheric initial conditions. The sea surface conditions are the same for each run. They are derived from an observed climatology in the first case, and from an earlier coupled ocean atmosphere climate scenario for the second case. The climate scenario used was the so-called SRES-A2 one, corresponding to a relatively high emission scenario.

Concerning impact of climate change on french frost design method of roads, data processing consisted in the calculation of the temperature anomaly between the mean winter temperature on the sets of simulations of the future period and on the sets of simulations of the current period. This anomaly has been added to the daily average temperature extracted from a measured database on the two reference winters of the current period. This work allowed to calculate the reference index expected of the future period.
The decrease of the reference frost index values until 2100 will involve the fact that frost checking will not be necessary in the future. Thermal constraints will become less important than mechanical ones even in the North East of France.

Concerning impact of climate change on winter maintenance, different processings of the snow data have been carried out on the current period and on the future one. This work allowed to forecast the evolution of different indicators : snow occurrence, consecutive snow days and snow intensity. Globally, the snow data shows that winter constraints will drastically decrease during the coming century. This reduction will involve different types of impacts on the winter maintenance activity. The first one will interest the winter maintenance global cost. As snow occurrence, snow intensity and snow duration will decrease, designing of winter maintenance services will change. As an example, the most visible consequencies will be the reduction of staff, of equipments (winter maintenance vehicules, snow plough, etc..), buildings and particularly de-icer shelters, brine manufacturing devices, which will adapt to the number of winter maintenance operations. Moreover, the duration of standby operation will probably be reduced, because the definition of the "winter period" will be reduced too. Another impact will be the improvement of management of winter maintenance staff, because of the reduction of the number of important and consecutive snow falls.
Thanks to the data processing, it seems that a global reduction of winter maintenance of about 50 % could be assumed. It allows to assume the same decrease ratio for buildings surfaces, de-icers shelters, number of operations and de-icers spreading.

Acknowledgements

The IMFREX project (which produced the data used in this study) has been partly supported by the French department of Ecology and Sustainable Development

1. Introduction

The purpose of this work is to try to quantify the evolution of practices in frost design method and in winter maintenance of roads in France for the coming century. The work is based on climate simulations from the database of the French IMFREX project. It uses the ARPEGE-CLIMAT model of Météo-France to simulate climate evolution during the 21st century under an A2 scenario of the IPCC (Intergovernmental Panel on Climate Change). This paper describes first, the current conception and maintenance of french pavements. Then, the climate simulations obtained from the database of IMFREX project. Finally the impact of the decrease of winter constraints on frost design method and winter maintenance in the future is discussed.

2. French pavements in winter : current conception and maintenance.

2.1. Winter maintenance in France

Road maintenance services are often designed to fit with the winter constrainsts to which the netwok is submitted to. Winter maintenance could be characterized by a fixed and a variable part :

- The fixed part is a narrow fonction of the climatology of the place (average expected winter maintenance) , the characteristics of the network (transversal slope, sinuosity, altitude, nature of the pavement surface, etc) and the nature of expected winter events (snow, black ice, snowdrift). This part could be built with the Hi indicator, which is defined as a function of number of snow occurrence, black-ice, etc (figure 1). This part designs buildings, equipments, materials, and financial ressources.

- The variable part corresponds strictly to the operational part of winter maintenance. It is totally dependant of the meteorological and road events met, on a statistical point of view : number and importance of snow falls, number of black ice or icy precipitation situation, occurrence period of the event (weekend, holidays...). This variable part could be approched by a normalized winter maintenance index (IVH_{100}), calculated from meteorological parameters, characteristic of how severe was maintenance over the winter(figure 1).

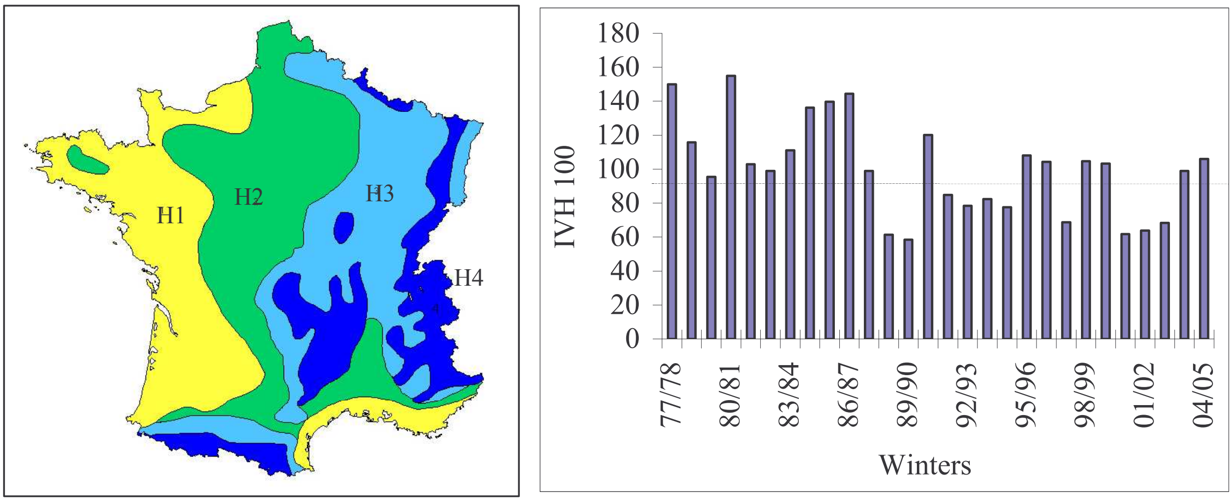
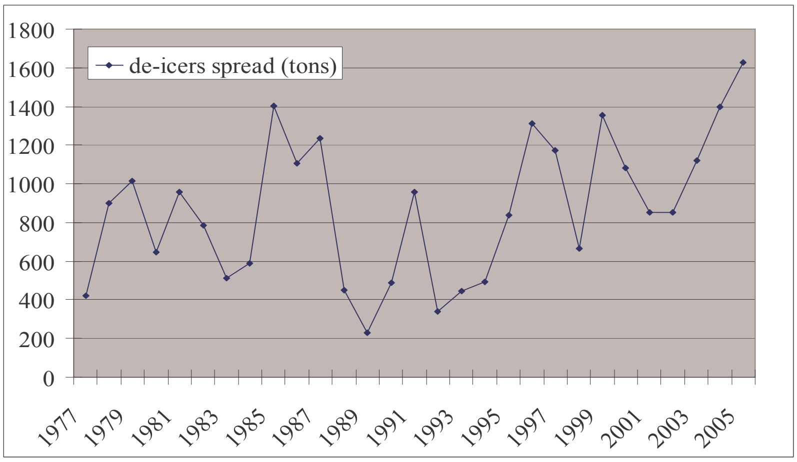


Figure 1 : Hi areas and normalized winter maintenance index (IVH_{100}) calculated for the meteorological station of Clermont-Ferrand.

Design of winter maintenance services is defined from meteorological criteria. It particularly takes into account snow occurrence (since means allocated to snow allow also to cover black ice events). Two parameters are important : the snow intensity and the snow duration. They are part of the "non-overtaken" limit condition as mentionned in technical winter maintenance guides. This limit condition is the one below which road manager can reach the announced service level, with his own means (winter maintenance engine and staff). Above this limit, he has to mobilize additionnal means (sub-contractors) or reduce service level.



During winter period, road managers can apply de-icers to ensure users safety. The amount of de-icers spread during winter maintenance activity on the French network, ranges between 250, 000 tons and 1, 700, 000 tons in accordance with winter severity (Figure 2).

Figure 2 : Amount of de-icers spread on the French Network since 1977

2.2. Current frost design method in France

The thermal behaviour of the road structures in winter can have a major influence on their design, in accordance with frost suceptibility of their subgrade and winters severity the pavement might have to withstand during its lifetime. The frost design method [1] consists in a “checking” with respect to frost/thaw phenomena. It makes sure that the roadway designed from mechanical calculations can withstand a given winter chosen as a reference, without notable damage.
Verification of the frost/thaw behaviour involves comparison between :
- the atmospheric frost index chosen as reference (IR), that characterizes the severity of winter, according to the area, against which the structure has been chosen to be protected. The winter chosen as the reference depends on road manager policy. Two reference indexes are usually considered : exceptional winter frost index (the highest index since 1951) and non exceptional rigorous winter (winter with 10 years occurrence).
- and the atmospheric allowed frost index that the road structure is able to withstand (IA). This index is evaluated according to the frost susceptibility of the subgrade, the thermal protection and mechanical function fulfilled by the pavement.

The pavement structure is designed so that the allowed frost index IA of the pavement is greater than the reference frost index IR. In the opposite case, the pavement structure has to be modified, until a positive frost testing is reached. It could be obtained either :

- by a reduction of the frost susceptibility of materials (treatement of soils)
- by an increase in the thickness of the frost-resistant layers (capping layer in particular)

IR can also be greater than IA if the setting of thaw barriers is accepted to protect the structure during thaw periods. This solution is usually applied to secondary network.

Frost design method has a major influence on pavement design in the North East of the France, where the reference atmospheric index are important (figure 3). Most structures, once the mechanical design done, have to be "over-designed" to take into account specific thermal stress.

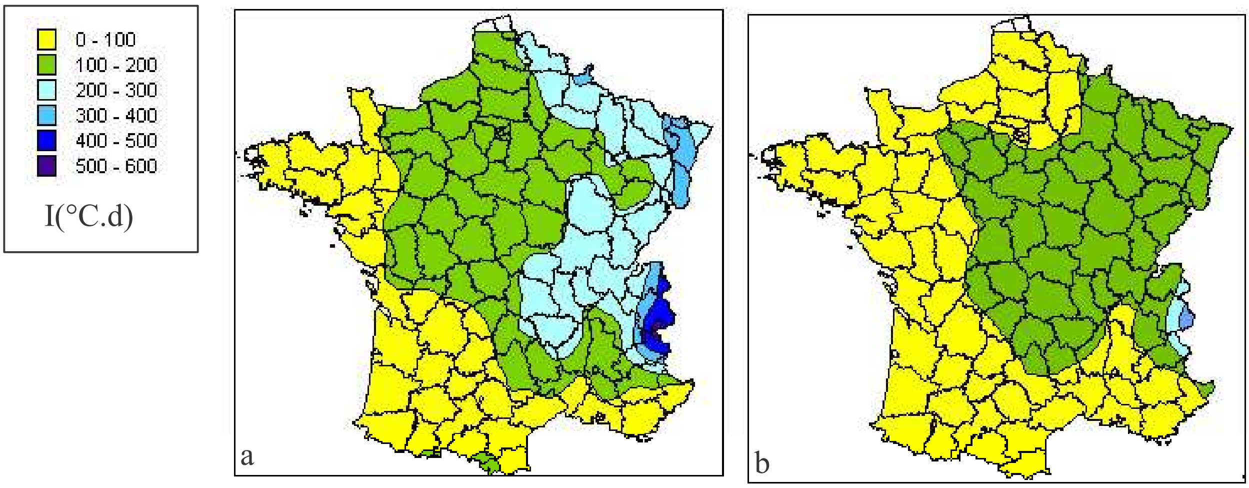


Figure 3: Map of the exceptional winter (a) and the non exceptional rigorous winter (b) frost indexes (°C.d)

Table 1 shows, for two types of structures, one of bituminous materials and the other of hydraulic treated ones, and for two capping layer natures (granular or treated material), calculations of the needed thickness of capping layer, only mechanically and with the thermal checking, for both reference frost indexes of Strasbourg city.
The assumptions for these calculations are the following ones :

- a definied traffic category greater than 14 millions of trucks (TC630),
- a good platform quality with a bearing capacity of 120 MPa (AR2, PF2),
- an highly frost suceptibility of the subgrade.

The calculations have been made from the abacus of the *French design manual for pavement structures* [1]. It allows to calculate thickness of the capping layer, depending on its nature, needed to protect the frost susceptible soil, as a function of frost reference index.

Table 1: Thickness of capping layer needed in accordance with reference frost index

Types of strutcures	Thickness needed mechanically (m)		Thickness needed thermally (m)			
			Non rigorous exceptionnal winter of Strasbourg city IR = 175°C.day		Exceptionnal winter of Strasbourg city IR = 350 °C.day	
	Granular materials	Treated materials	Granular materials	Treated materials	Granular materials	Treated materials
Bituminous material GB3/GB3	0,50	0,35	0,53	0,46	0,87	0,76
Hydraulic bound material GC3/GC3			0,37*	0,33*	0,69	0,60

* cases whitout thermal overdesign

Different observations could be done here :

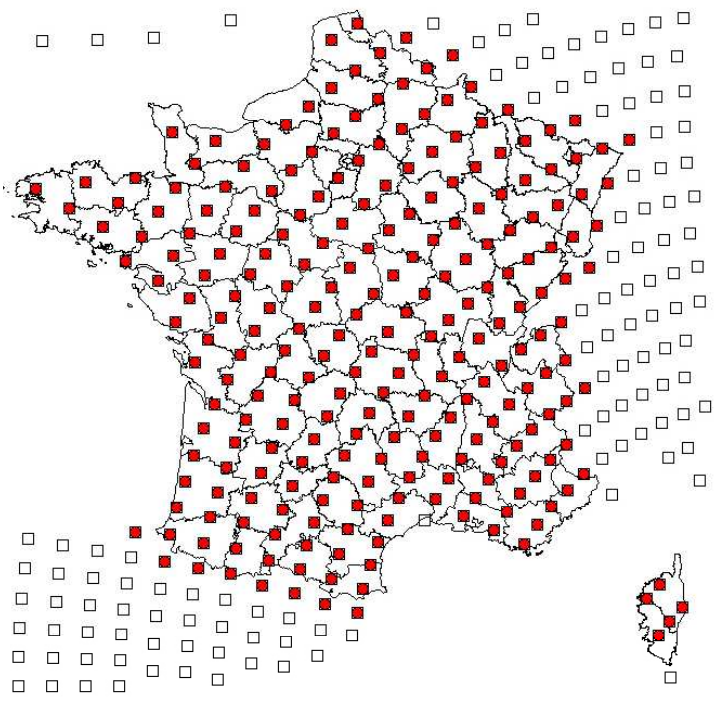
- In the case of IR = 175°C.day, the increase of the thickness of the capping layer related to thermal stress is not necessary for the hydraulic binder treated pavement. Indeed, the thickness needed mechanically is greater than the thickness needed in accordance with frost/thaw behavior. For all other cases, overdesign versus thermal stress is necessary.

- The thickness of the necessary capping layer needed thermally is more important for bituminous structure than for hydraulic treated ones, indeed, these lasts are thicker to withstand the same mechanical constraints.

- Thermal protection afforded by the frost-resistant materials of the capping layer depends on their nature : treated materials are more protective than granular ones.

3. The climate change in France : available database

The climate simulations used here were obtained from the database of the French IMFREX project (http://medias.cnrs.fr/imfrex/). The climate model used was the version 3 of the ARPEGE-CLIMAT atmospheric model [2]. The model was used with a variable grid : the horizontal resolution was better over Europe than in the rest of the world. The one over France being around 50 km [3]. As this project was originally designed for the study of extremes events three sets of simulations were done for the current condition (1961-1999) and the future one (2071-2099) in order to increase the probability of this kind of events. The three members of each ensemble differ only by the atmospheric initial conditions. The sea surface conditions were the same for the three runs. They derived from an observed climatology in the first case, and from an earlier coupled ocean atmosphere climate scenario in the second one. The climate scenario used was the so-called SRES climate scenario, corresponding to a relatively high emission scenario.
The climate scenario used was the A2 scenario of the IPCC (Intergovernmental Panel on Climate Change), corresponding to a relatively high emission scenario, with an important impact in terms of temperature change. In this scenario, CO_2 emissions keep on growing till CO_2 concentration nearly reach 850 ppm at the end of this century. It is more than twice the current concentration.



Different types of data were available for upload from the website. As an example, number of frost days, snow occurrence, precipitation, air temperature are presented daily for the periods 1961-1999 and 2071-2099.

These data were available on 360 points over the French territory but also outside the borders. Among the available data, only, 240 points, in red in figure 4, have been calculated in this paper.

Figure 4 : Location of data available on the IMFREX website

3.1. Impact of climate change on French frost design method of roads

Climate change will directly impact atmospheric temperatures during the winter period, and as a consequence, the reference frost index, design factor in the French method.

3.1.1. Data processing

- <u>Methodology</u>

The average daily temperature was calculated from the mean of minimal and maximal temperature on the three sets of simulations, for the current and the future situations. For each point of the IMFREX grid, a temperature anomaly has been calculated in the winter period, defined from the 1st of november to the 31th of march. This anomaly represents the difference between the mean of the average daily temperatures of the 3 sets of simulations of the future situation and the mean of the

average daily temperatures of the 3 sets of simulations of the current condition.
In order to avoid artefacts due to a change in the number of meteorological stations taken into account, it has been decided to work on a regular grid over France. The work was divided into the following steps :

- Extraction on a 0,1° grid of the average daily temperatures measured on two representative winters of the period 1961-1999.
- Interpolation of the temperature anomalies from the IMFREX grid to the 0.1° grid.
- Calculation of the new values of temperature on the grid (including the anomaly) for the two representative winters.
- Calculation of the frost indexes from this average daily temperature, without temperature anomaly for the current condition (figure 3), and taking into account the anomaly to featured future situation.

The two winters chosen as reference are :

- winter 62-63, which is the exceptionnal rigorous winter for the major part of french territory, except for the south west where, winter 84-85 was more severe.
- winter 86-87, which is near from the non exceptional rigorous winter

This method allows to forecast, from this two winters, considered as the two reference winters of the current period, the foreseeable reference winters of the future period.

- Calculation details

The calculation of the maximal atmospheric frost index of a given winter is done as following :
- Calculation of the average daily temperature (°C) :

$$Tm(d) = \frac{Tn + Tx}{2}$$

where, Tn is the minimumdaily temperature of day d, measured under shelter between 18h UTC the day (d - 1) and 18h UTC the day (d).
Tx is the maximum daily temperature of day d, measured under shelter between 6h UTC the day (d) and 6h UTC the day (d+1).

- Calculation of elementary frost index for isolated frost period :

$$I = \left| \sum_{d=1}^{d=n} Tm(°C) \right|$$

where d =1 is the first day where the average daily temperature becomes negative and d=n , the last day where the average daily temperature is negative.

- Calculation of the cumulated indexes : for road design, elementary indexes are cumulated over the winter as described in the French standard NF P 98-080-1 :
If IT(i) < IF(i),
Case 1 : IF (i) > 25 °C. d
if IT(i) < IF(i+1)
then frost periods are cumulated : I = IF(i) - IT(i)+ IF(i+1)
if IT(i) > IF(i+1)
then frost periods IF(i) or I(i) et IF(i+1) are separated.
Case 2 : IF (i) < 25 °C. d
if IT(i) < 10 °C. d
then then frost periods are cumulated : I = IF(i) - IT(i)+ IF(i+1)
if IT(i) > 10 °C. d
then frost periods IF(i)et IF(i+1) are separated
with IT is the thaw index, IF the frost index and I the frost cumulated index. If frost indexes are cumulated, I exists, and then IF(i) becomes I(i) in the algorithm.

- Selection of the maximal frost index, among the different frost cumulated indexes for each point over the 0,1° grid, for both winters.

- Results

Calculation of frost reference indexes for the future situation is presented in Figure 5. These maps must be compared to the maps of the current condition of figure 3. They show a drastic decrease of the frost index over most part of France. One can notice that the grid accuracy of the grid does not allow to properly take into account the relief on the maps.

It must be noted that this figures are based on a basic shift of the temperature, based on the mean temperature anomaly. The evolution of extremes temperature will not necessarily follow the evolution of the mean temperature. This point should be examined further and may slightly impact the results presented here.

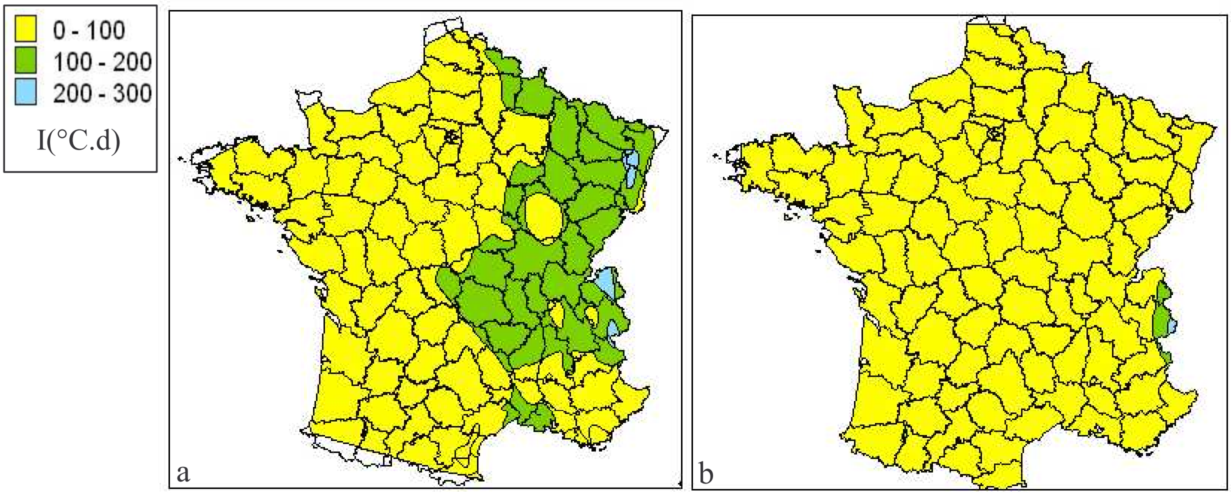


Figure 5 : Map of the exceptional winter (a) and the non exceptional rigorous winter (b) frost indexes expected in the future situation

3.1.2. Impact of climate change on frost design for the years 2070-2100

The same table as the one in first part presented below. The increase of the thickness of the capping layer is not necessary in accordance with thermal constraints for the major part of cases, with the reference frost index expected for the future situation in Strasbourg, respectively 100 et 200°C.day. Exceptionnal frost index of the future period becomes approximatively non rigorous frost index of the current situation.
Nevertheless, these cases could not be extended to all existing structures. For example, weak trafic structures are thinner for mechanical constraints, so frost verification could still be necessary in the future. This point can be discussed because, in the same time, theses structures are more often designed for the non rigorous exceptionnal winter.

Table 2 : Thickness of capping layer needed in accordance with reference frost index expected.

Types of structures	Thickness needed mechanically (m)		Thickness needed thermally (m)			
			Non rigorous exceptionnal winter of Strasbourg city IR = 100°C.day		Exceptionnal winter of Strasbourg city IR = 200 °C.day	
	Granular materials	Treated materials	Granular materials	Treated materials	Granular materials	Treated materials
Bituminous material GB3/GB3	0,50	0,35	0,33*	0,29*	0,58	0,50
Cement bound material GC3/GC3			0,19*	0,17*	0,42*	0,37

* cases whitout thermal overdesign

The comparison of maps of the exceptional reference frost index between the two periods (figure 3a and 5a), allow to quantify the number of square kilometers of France (that is to say the network's part as french network is considered regularly distributed over the territory) for which, frost checking would become not necessary for the main network. For example, for exceptionnal frost index, the surface of "200 to 300 °C.day" is reduced from 110 000 km^2 to 5000 km^2 between the two periods and the surface of "300 to 400°C.day" and more becomes nil in the future situation. So all roads which must currentlty be over-designed because of thermal constraints, will not be so tomorrow. As, for a 2*2 road, the cost of 1 centimeter of granular capping layer is approximatively of 5000 euros per kilometer, a significant saving of money could be obtained for the conception of the future network.

3.2. Impact of climate change on winter maintenances activities

3.2.1. Calculated data

Data of snow precipitations, from large scale and convective origin, have been summed up for this work. Different processings of the data have been carried out : snow occurrence, consecutive snow days and snow intensity. These data concern snow fall, and not the way of the snow is being held on the surface pavement.

- Number of daily snow occurrence

The same methodology used for frost index has been employed here.
An average number of daily snow occurrence has been calculated, in each point, on the three sets of simulations, for the current condition and the future situation. The difference between mean number of daily snow occurrence in the future situation and in the current condition, has been interpreted as a rate of decrease of snow occurrence. This rate has been spacialized and affected onto the meteorological stations (86 stations) where the number of snow occurrence had been measured, during the period 1996-2006.
This methodology allows us to realise maps presented in figure 6, using krigging.
The map on the left side, presents daily snow occurrence for an average winter of the current period and the one on the right side, presents daily snow occurrence expected for the future period.

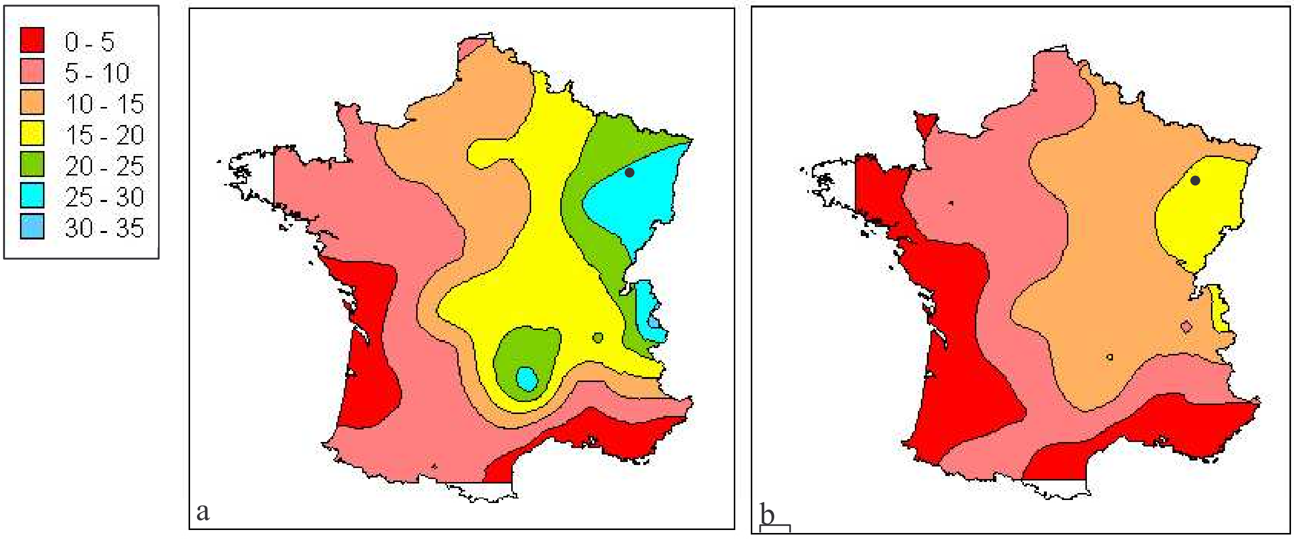


Figure 6 : Number of daily snow occurrence in the current (a) and future(b) periods

The difference between the two maps is noticeable, with, for example, a number of daily snow occurrence of about 25 in Nancy (•)in the current period compared to about 15 in the future, that represents globally, reduction of about 1/3. These observations can be explained by the fact that, even if precipitations in winter period will increase in the future, as temperature increase too (an increase of about 3°C in average between both periods has been shown in the calculation of future frost indexes), number of snow occurrence will decrease.

- Maximal number of consecutive snow days

Following the same methodology, we work on the number of consecutive snow days, as an interesting indicator of winter maintenance difficulty. Maps in Figure 7, show the maximum number of consecutive snow days in the current period (measurements on meteorological stations) and in the future situation.
The maximal number of consecutive snow occurrence will be about 6 in the future, while it has values greater than 10 in the North East, in the current period (15 consecutive snow days measured in Nancy during winter 2004-2005). The situation of the North-east of France in the future scenario will be equivalent to the current one in the South-West.

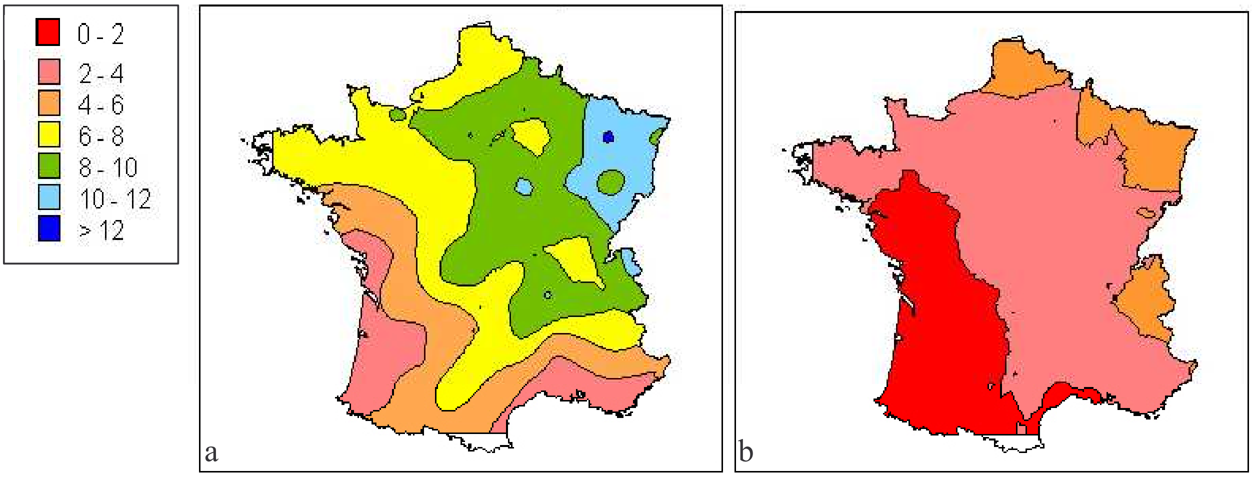


Figure 7 : Maximum number of consecutive snow days : current (a) and future(b) situations

- <u>Number of snow occurrence in accordance with snow fall intensity</u>

Intensity of snow precipitation is also an important indicator of winter maintenance difficulty. For these data, only sets of simulation were processed, because of a lack of measurements on the current period. The work has consisted in assessing the evolution of the parameter intensity or more exactly snow height fallen during 24 hours, between the two situations. For this purpose, Figure 8 shows the evolution of the average number of snow occurrence (over the 240 points) in accordance with intensity categories, for the current period and the future one. Figures have been normalized on the two periods to take into account the fact that the current period is longer (40 years) than the future one (30 years).

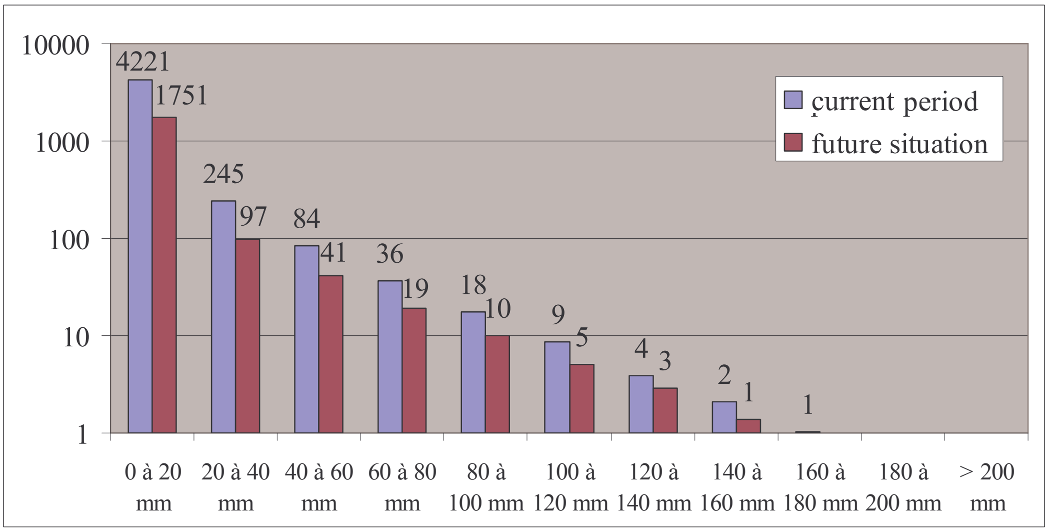


Figure 8 : Average number of snow occurrence in accordance with intensity categories

The graph shows that the intensity of snow fall will be strongly reduced in the coming century. Weak intensites of snow fall will be a bit more reduced (factor > 2 until 60 mm globally) than great ones (factor < 2 from 60 to 200 mm).

3.2.2. Impact on climate change on winter maintenance for the years 2070-2100

Globally, snow data shows that winter constraints will drastically decrease during the coming century. This reduction will involve different types of impacts on the winter maintenance activity. The first one will interest the winter maintenance global cost. We can assume, as snow occurrence, snow intensity and snow duration will decrease, winter maintenance services will be adapted. As an example, the most visible consequencies will be the reduction of staff, of equipments (winter maintenance vehicules, snow plough, etc..), buildings and particularly de-icer shelters, brine manufacturing device, which will adapt to the number of winter maintenance operations. Moreover,

we can suppose that duration of standby operation will go down, because the definition of the "winter period" will change. Currently, winter period duration, is defined as the period during which, approximatively 95% of snow occurrence happen. This period is globally defined in France from the15th of november to the 31st of march. It might then extend, it will reduce from the 1st of december to the 15th of march for example.
The reduction will be of about 50% for buildings surfaces, de-icers shelters (number or surfaces), de-icers spreading. etc. Nevertheless, as there will be less events, roads users and managers will tend to be more and more requirering, will accept less risk of accident linked to meteorologic phenomena, and service levels will tend to increase. This assumption would show that the number of winter maintenance vehicles, number of operation or amounts of de-icers spread, will maybe not really decrease. Moreover, even if snow occurrence will decrease, the number of winter maintenance vehicles will not really decrease in a significant part, because of black-ice events which, despite of the temperature increase, should always exist.
Another important impact will be the management of the staff. In fact, reduction of winter constraints will improve the management of winter maintenance staff. Currently, legall framework provides often some difficulties in the service organisation, particularly in the case of important and consecutive winter events, since the staff is obliged to work during a time greater than the legal hours and after to be in rest period, that provides often staff lack.
Two assumptions can co-exist for the future :

- the "non overtaken" limit condition will stay the same and the sub-contractors and the complementary means will be less mobilized.
- the "non overtaken" limit condition will reduce, then the design of the winter maintenance service will reduce in the same way.

For the second assumption, a global saving of money could be calculated. If we assume that the global reduction of winter maintenance activity will be of about 50%, we can estimate the cost of the winter maintenance of one kilometer of motorway for example in the future. Currently, the global cost communicated by a French private motorway company is approximatively of 8000 euros per kilometers, we can easily calculte the expected cost of 4000 euros.

4. Conclusion

Snow data and frost indexes processing, globally shows that winter constraints will decrease drastically during the coming century. This reduction will impact the winter maintenance activity, but also on the conception of pavements. The main impact is financial, with a reduction of investments in roads conception, particularly concerning capping layer, for about a quarter of the French territory. Concerning winter maintenance, the decrease of the global cost is more difficult to estimate, because winter maintenance could hardly be disconnected by road maintenance and because different future trends could be outlined. However, we can think that the activity will decrease more or less by an-half by the end of the 21st century.
These preliminary works will have to be followed, refining climate scenari (taking into account their uncertainties in particular), with a better quantification of the relationship between meteorological parameters and winter maintenance activity, and taking into account others context elements such as technics and trafic evolutions.

Acknowledgements

The IMFREX project (which produced the data used in this study) has been partly supported by the French department of Ecology and Sustainable Development

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