Climate Change – Ramifications for Structural Road Design

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ABSTRACT: What has been largely overlooked to date is the subject of the coming climate changes in relation to structural road design. The effects of climate change on asphalt road design will be particularly noticeable. Because of the strongly temperature-dependent mechanical properties of asphalt as a building material, climate shifts in the surrounding environment may have a considerable effect on the durability of asphalt pavements. A case-oriented, economically and ecologically sustainable dimensioning can only be ensured through consideration of all of the factors that influence the durability of the asphalt roads. In the process, the prognosis for the future progression of these influences increases in significance. For Dresden and the surrounding area (Germany/Saxony), the first investigations into the effects of prospective climate changes on the durability of asphalt road constructions were conducted. The prognoses for the actual time-frame for usability of the asphalt roads lead one to expect that, if climate changes are not taken into consideration for the dimensioning of such constructions, they will suffer early substantial damage.

KEY WORDS: Climate change, thermal prediction simulation, durability of asphalt pavement structures

1 INTRODUCTION

Global climate change is one of our society's most current and controversial topics. The causes of climate change occurring today are many; however, it is clear that the changes are, at least in part, most likely due to human activity. During the 2nd half of the 20th century, one could observe the increase in both maximum and minimum air temperatures, and that the rise in daily minimum air temperatures was higher than that of maximums. In addition, the number of hot days increased, while the number of cold and freezing days decreased. It is highly probable that this development will continue through the 21st century [IPCC 2007]. What has been largely overlooked to date is the relation between the coming climate changes and structural road design. The effects of climate change on asphalt road design will be particularly noticeable. Because of the strongly temperature-dependent mechanical properties of asphalt as a building material, climate shifts in the surrounding environment may have a considerable effect on the durability of asphalt pavement structures. This pertains not only to conspicuous damage such as the development of ruts, the appearance of which will increase in summer due to climate-induced rises in temperatures, but also to the damage (fatigue) to the actual material of the asphalt pavement structures. While ruts may occasionally present a distinct threat to traffic safety, their repair is by far less time and cost-intensive than the restoration of fatigued asphalt base layers. In times when budgetary appropriations are limited for the construction and maintenance of infrastructure in general, and of road pavements in particular, associated with steadily rising traffic volume, individual, problem-specific dimensioning is becoming increasingly necessary. Such case-oriented, economically and ecologically sustainable dimensioning can only be ensured through the consideration of all factors that influence the durability of asphalt pavements [Kayser 2007, Kayser 2008]. In the process, the prediction of the future progression of these influences increases in significance.

2 CLIMATE-RELATED CHANGES

The extensive measurement and monitoring of significant climate-related parameters clearly shows that the global mean temperatures of the near-surface strata have risen since instrumentals records started in 1850. The mean temperature increase in the 20th century was approximately 0.6 K ±0.2 K. Moreover it is observed that the rise in night-time daily minimum air temperatures is double (approximately 0.2 K per decade) the rise in day-time daily maximum air temperatures. In many regions this resulted in shorter frost periods. This temperature rise due to global warming has become markedly noticeable mainly for the last decades. For example, at least eleven years of the period of 1995 to 2006 were recorded as the twelve warmest years since 1950 [IPCC 2007]. Precipitation in the northern hemisphere (>30°N) increased by 0.5 % to 1.0 %. With +2 % to +4 %, the rise in the frequency of occurrence of very heavy precipitation events in these regions was far more distinct [IPCC 2007]. According to [IPCC 2007] it is probable that the observed climate changes can be attributed to anthropogenic factors to a considerable extent. The distinct rise in greenhouse gas concentrations since the 1950s and their impact on the energy balance of our climate system resulted in a positive radiative forcing with subsequent warming of the near-surface strata. Climate changes may have rather different impacts on different regions. While the global mean of ground level air temperatures has increased by approximately 0.6 K [IPCC 2007] in the 20th century, the European mean increased by even 0.8 K [Leuschner and Schipka 2004]. In Germany, an analysis of climate development for the same period reported an increase of 0.9 K [Hulme and Sherd 1999, Schönwiese et al. 2003]. To predict the future development of our climate system, [IPCC 2001] gives various emission scenarios (Special Report on Emissions Scenarios - SRES). These emission scenarios rest on predictions of the future development of the world economy. The scope of the scenarios is wide and includes an approach assuming rapid economic growth with intense use of fossil energy sources and also an assumption of decreased material consumption, the use of clean and resource-efficient technologies and environmental sustainability. All scenarios neglect influences that result from the implementation of the United Nations Framework Convention on Climate Change - UNFCCC or the Kyoto Protocol. Mathematical modelling and the prediction of future climate developments show that global warming will continue to rise by approximately 0.1 K / per decade even without a further increase of greengas concentrations and thus constant radiative forcing taking the year 2000 as a basis. If, however, greenhouse gas emissions will increase in accordance with the IPCC scenarios, an average global warming of approximately 0.2 K to approximately 0.4 K will be expected.

3 THERMAL PREDICTION SIMULATIONS FOR ASPHALT CONSTRUCTIONS

Special simulations are necessary to estimate the effects of prospective climate changes on the durability of asphalt road constructions. Starting from the development of relevant climate parameters predicted by the related IPCC scenarios, the future thermal conditions in asphalt pavement structures can be simulated using the heat balance equation. The climate parameters relevant to the simulation of the thermal conditions of circulation areas in accordance with the heat balance of road surfaces illustrated in Figure 1 include global radiation, near-surface air humidity, wind speed, amount of precipitation and cloud amount. Initial tests made at the Institute of Pavement Engineering at Dresden university of Technology analysed possible effects of future climate changes on the thermal stress of asphalt road pavements and their material durability. Thermal simulations with the climate data predicted and provided by the models and data group of the Max Planck Institute of Meteorology, Hamburg, and the IPCC emission scenario A1B [Lautenschlager et al. 2006] have been conducted.

Definition of the emission scenario A1B: The A1 family of scenarios describes a future world with rapid economic growth, a global population peaking in the mid-21st century and declining thereafter and the quick spread of new and efficient technologies. Fundamental topics of importance are the convergence of regions, the development of competence for autonomous action and also extensive cultural and social interactions worldwide with strong convergence of per capita incomes between rich and poor countries. The A1 family of scenarios has three subsets that describe different foci of technological changes in the energy system. The three A1 groups have differing technological emphases: emphasis on fossil fuels (A1FI), emphasis on non-fossil energy sources (A1T) and a balanced emphasis on all energy sources (A1B). The research staff at the Max Planck Institute of Meteorology in Hamburg carried out model computations for emission scenario A1B in two runs (A1B run 1 and A1B run 2) with different start conditions. The result is a range of future developments of the climate environment.

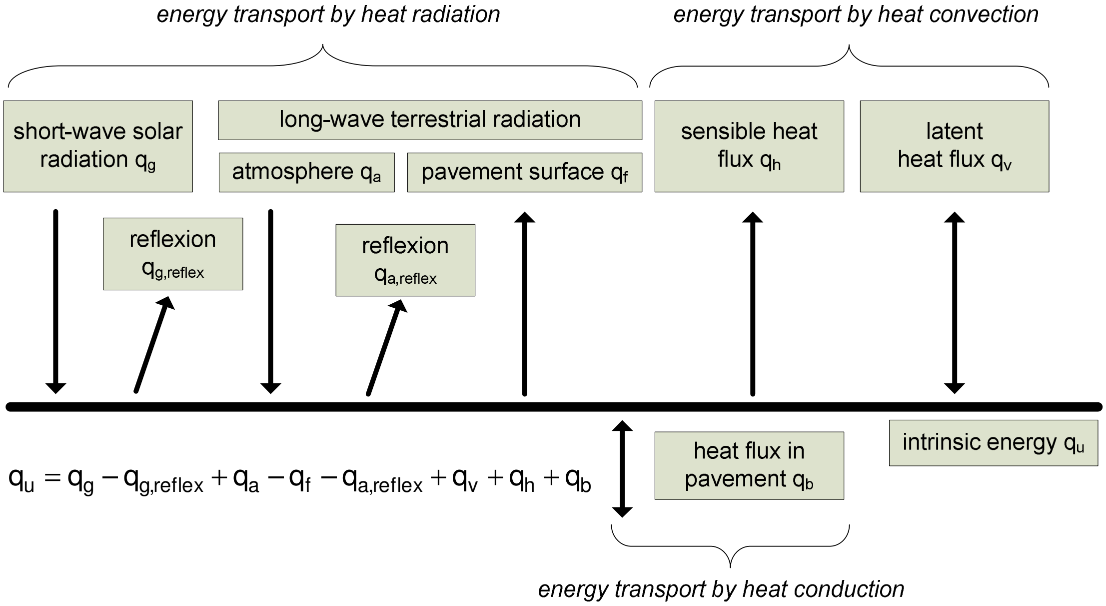
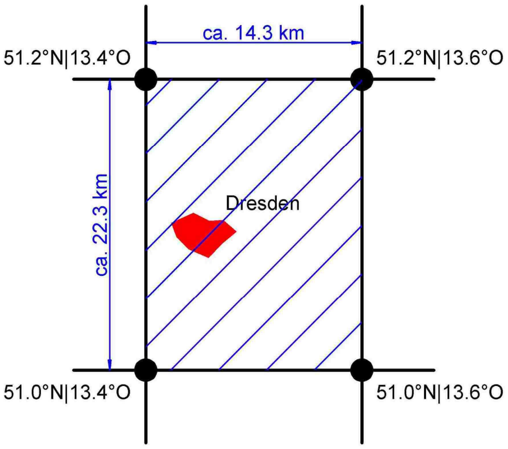


Figure 1: Schematic diagram of all energy and heat flows relevant for the simulation of road surface temperatures [Kayser 2007].

The predicted changes of the ambient climatic conditions of the two model computations of scenario A1B were used to numerically compute the surface temperatures and the temperatures in the asphalt pavement. Simulations have been carried out for the region Dresden and surroundings (longitude: 13.6° - 13.8°; latitude: 51.0° - 51.2°) for the period 2001 - 2069 (Figure 2 – left). The selected region has a total of four grid points and covers an area of approximately 318.9 km². The presented results of the thermal simulations are obtained with the mean values of the relevant climate parameters of the four grid points and are thus averaged over the area. Climate simulations C20 (Climate of the 20th Century) have been integrated for the period 1980 - 2000 as reference values for the assessment of the thermal stress changes of asphalt pavement structures resulting from the modelling of scenario A1B [Lautenschlager et al. 2008]. Due to the complexity of the heat balance equations and the long simulation period of 90 years, the simulations have been limited to a one-dimensional road construction-atmosphere system. Three parameter variants have been analyzed of the thermophysical material characteristics (Figure 2 – right). Individual parameters of the three variants have been defined such that the influence of the climatic ambient conditions on the temperatures of the asphalt road construction is as strong as possible (VAR3) and as weak as possible (VAR1) in relation to the reference variant (VAR2).



variant-ID	VAR1	VAR2	VAR3
parameters for asphalt			
reflectance (short-wave solar radiation) [-]	0.800	0.850	0.900
reflectance (long-wave terrestrial radiation) [-]	0.975	0.950	0.925
thermal conductivity [W/m/K]	1.25	1.05	0.75
specific heat capacity [Ws/kg/K]	1,000	878	650
density [kg/m³]	2,500	2,240	2,000
conductibility of temperature [cm²/h]	18.00	19.22	20.77
parameters for sub base			
conductibility of temperature [cm²/h]	42.68	42.68	42.68
parameters for sub grade			
conductibility of temperature [cm²/h]	46.54	46.54	46.54

Figure 2: left: Schematic diagram of the examined region; right: thermophysical material properties of the three parameter variants

4 CHANGES OF CLIMATIC PARAMETERS RELEVANT TO THE SIMULATION

The analysis of the climatic development predicted by the Max Planck Institute of Meteorology in Hamburg for emission scenario A1B for the area under investigation (Dresden and its surroundings) shows noticeable climate changes in the future. For example, it is expected that the 30-year mean near-surface air temperature will continually increase in the future. On the basis of the 30-year mean temperature (Tmean) for the period 1980 to 2009 it is expected that the 30-year mean air temperatures will increase by approximately 0.9 K by the end of the first half of this century and by approximately 1.6 K to 1.8 K by the end of the investigation period (2069) (Figure 3). The development of the 30-year mean air temperature minima (Tmin) will be far more drastic. An increase of approximately 1.7 K to 2.1 K is predicted already for the next 30 years. The increase will be even 5.9 K by the end of the investigation period (2069) (Figure 3). As far as the 30-year mean air temperature maxima (Tmax) in the area under investigation are concerned, increases are expected only in the second third of this century.

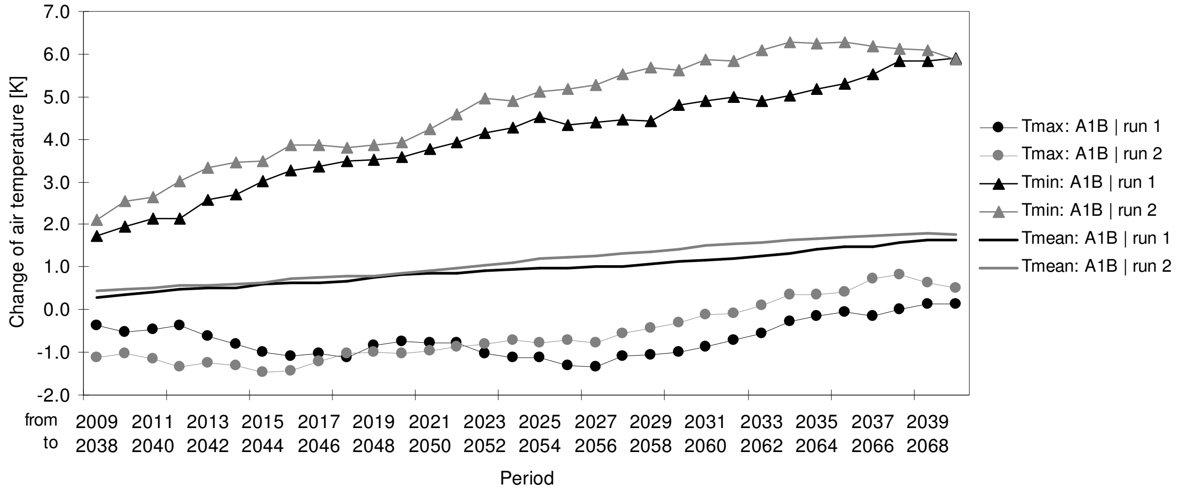


Figure 3: Predicted absolute changes of the 30-year near-surface, mean air temperatures related to the mean value of the period 1980 - 2009.

By the end of the investigation period (2069), however, the 30-year mean air temperature maxima will increase by approximately 0.1 K to 0.5 K according to predictions (Figure 3).

According to the predictions of emission scenario A1B, a decrease of the global radiation intensity is expected. This is a reduction of a significant component of the energy input into the road surface. This radiation decrease can be explained by increasing cloudiness. Increasing cloudiness causes the atmospheric counter-radiation to increase as a result of the higher emissivity of the atmosphere for infrared radiation. At the same time, it intensifies the greenhouse effect thus warming the earth's climate and further intensifying the atmospheric counter-radiation. Further changes of the other simulation-relevant climate parameters (air humidity, precipitation and wind velocity) are predicted for the next years.

5 CHANGES OF THERMAL STRESS IN ASPHALT PAVEMENT STRUCTURES

Some significant changes of the climate parameters relevant for thermal simulations of asphalt pavement structures are expected in the next years of this century assuming the IPCC scenario A1B. Since these climate parameters have a direct effect both on the surface temperatures of the pavement and the temperatures in the individual asphalt layers, it is expected that the thermal stresses in asphalt pavement structures will change, too. Figures 4 and 5 show the results of thermal prediction simulations as temperature differences related to the relevant average value of the reference period 1980 to 2009. These results clearly show that future climate changes will probably cause severe alterations in the thermal stress of asphalt pavement structures. For example, the mean pavement surface temperatures for parameter variant VAR2 (reference variant) for the next 30 years (2010-2029) are approximately 0.3 K to 0.4 K above that of the period 1980 to 2009 and for the years 2030 to 2059 approximately 1.0 K to 1.4 K higher. In the course of this century, a continuous increase in these 30-year mean temperatures (Figure 4) can be expected. As for the near-surface air temperatures, distinct changes are predicted for the 30-year mean minima of the pavement surface temperatures (Figure 4). These temperatures are approximately 1.4 K to 2.2 K higher in the next 30 years (2010 – 2039) than in the reference period (1980 to 2009). Predictions assume increases of the 30-year mean minima of the pavement surface temperatures by the end of the period under consideration of even up to 5.2 K in comparison with the reference period 1980 to 2009. The 30-year mean maxima of the pavement surface temperatures, however, will change less markedly (Figure 4). The tendency of future temperature developments is almost the same for different thermophysical asphalt properties of the three parameter variants. But differences of up to 0.5 K among the parameter variants and thus among the thermophysical asphalt properties, in particular for the absolute changes of the mean annual minimum and annual maximum temperatures, can be found (Figure 5). Design calculations are future expectations. However, currently the temperature conditions of the past are used to design the thermal stress of asphalt pavement structures according to [RDO-Asphalt 2009]. Even regular annual adjustments of these temperature conditions / temperature distributions will not suffice to take account of future changes (Figure 6) because, for example, the 30-year mean roadway covering temperatures for the years 2030 to 2059 will be by approximately 0.9 K to 1.2 K higher than those for the period 2000 to 2029. Design of asphalt pavement structures takes into account of the temperature load using vertical temperature profiles that represent the whole range of thermal stresses occurring in the asphalt pavement. The frequencies of the defined surface temperature classes demonstrate the frequencies of occurrence of these temperature profiles. Figure 7 summarises of the predicted developments of the 30-year frequencies of occurrence of three different surface temperature classes and shows the mean values of the two simulation runs of scenario A1B for parameter variant VAR2 (points) including the range of the scenario (error bars).

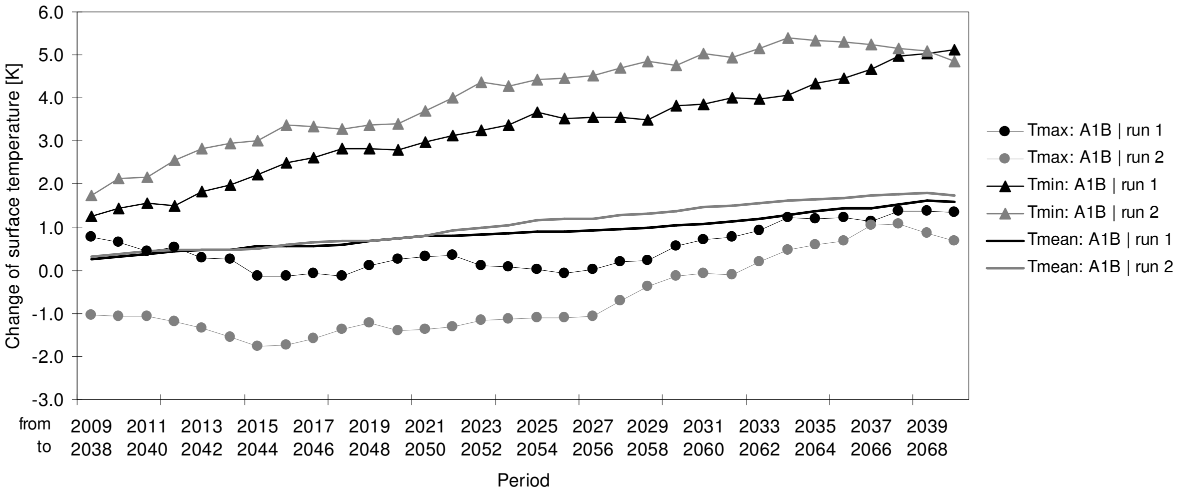


Figure 4: Predicted absolute changes of the 30-year mean pavement surface temperatures in relation to the average of the period 1980-2009 (VAR2).

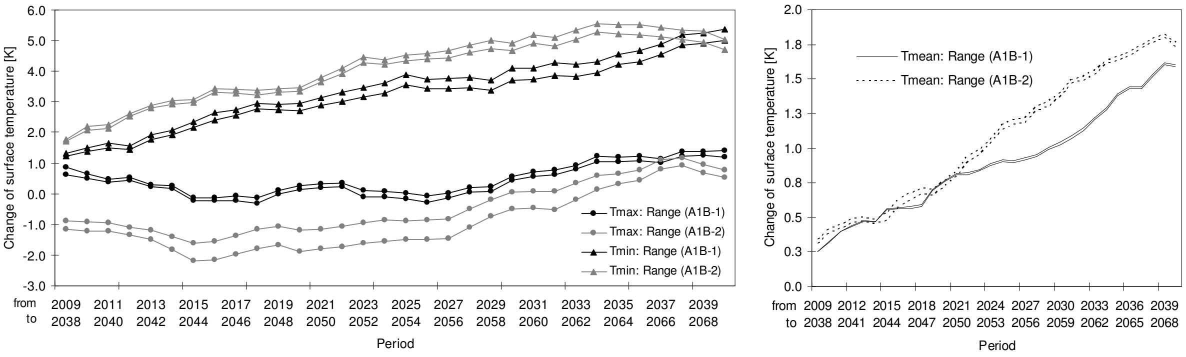


Figure 5: Range of predicted absolute changes of the 30-year mean pavement surface temperatures in relation to the average of the period 1980-2009 (VAR1 – VAR 3). left: range of annual minimum and maximum temperatures; right: range of mean annual temperatures

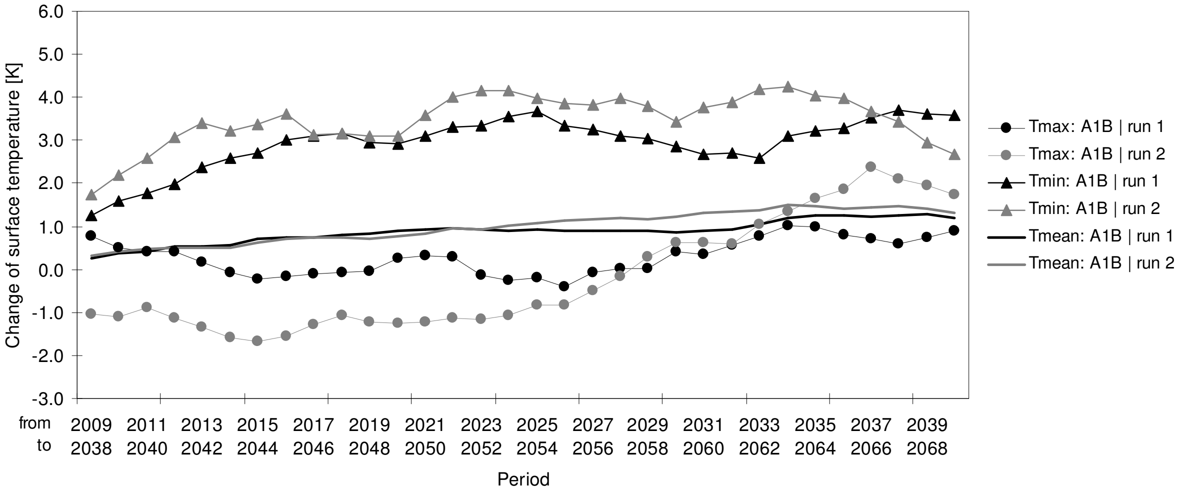


Figure 6: Predicted absolute changes of the 30-year mean pavement surface temperatures in relation to the average of the previous 30-year period (VAR2).

If a relation between the increases of the trendline (linear function) of the individual surface temperature classes and the relevant frequencies of occurrence for the reference period 1980 to 2009 is established, the future trends of the development of the individual surface temperature classes, which are illustrated exemplarily in Table 2 for parameter variant VAR2, on basis of the definitions shown in Table 1 can be described.

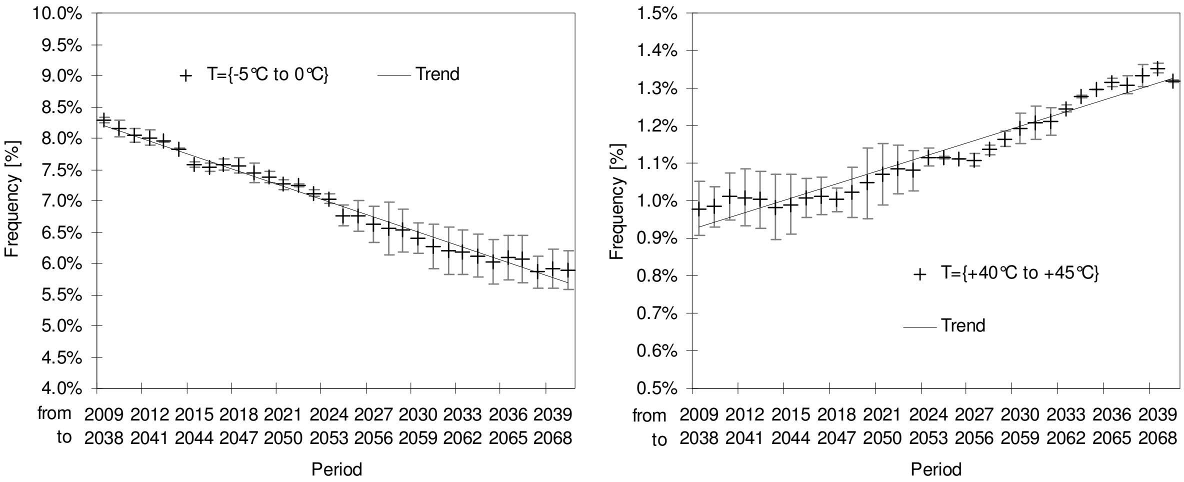


Figure 7: Predicted absolute changes of the 30-year frequencies of occurrence of three different pavement surface temperature classes. left: surface temperature class -5°C to 0°C; right: surface temperature class +40°C to +45°C

Table 1: Trend increase and trend description.

relative trend increase	trend
smaller -1.5%	significantly decreasing
up to -1.0%	decreasing
up to -0.5%	decreasing trend
up to +0.5%	almost constant
up to +1.0%	increasing trend
up to +1.5%	increasing
greater +1.5%	significantly increasing

Table 2: Trend development of the frequency of occurrence of surface temperature classes.

surface temperature class	trend according to Table 1
-20°C to -15°C	significantly decreasing
-15°C to -10°C	significantly decreasing
-10°C to -5°C	decreasing
-5°C to 0°C	decreasing trend
0°C to +5°C	almost constant
+5°C to +10°C	almost constant
+10°C to +15°C	almost constant
+15°C to +20°C	almost constant
+20°C to +25°C	almost constant
+25°C to +30°C	increasing trend
+30°C to +35°C	increasing trend
+35°C to +40°C	increasing trend
+40°C to +45°C	increasing
+45°C to +50°C	Increasing
+50°C to +55°C	significantly increasing
+55°C to +60°C	significantly increasing

6 EFFECTS ON THE DURABILITY OF ASPHALT PAVEMENT STRUCTURES

The future development of pavement surface temperatures reveals the necessity of taking into account climate changes and their predictions in the design of asphalt pavements. Climate change studies predict a rather probable continuous increase of asphalt layer temperatures in the next 60 years. Therefore one can deduce that asphalt pavement structures, which were sufficiently dimensioned for the climatic conditions of 1980 to 2009 and normally had a service life of 30 years, will definitely have a shorter service life. This can be proved by numerical fatigue prediction simulations in accordance with the procedure of the German Guidelines [RDO-Asphalt 2009]. The asphalt pavement structure chosen for the numerical stress and deformation analysis consists of the layers: asphalt surface course, 4 cm; asphalt binder course, 8 cm; asphalt base, 22 cm; sub base, 56 cm. The mechanical parameters employed are in accordance with those of asphalts used for calibration and described in [RDO-Asphalt 2009]. The layer module of the frost blanket or the E_{v2}-value of the soil, respectively, were defined as 140 N/mm² and 45 N/mm². The fatigue prediction took account of a total of 2,244 load conditions (11 axle load classes - frequencies in compliance with [RDO-Asphalt 2009]; 204 temperature classes - frequencies according to the thermal prediction simulations of scenario A1B and the three parameter variants of the thermophysical asphalt properties VAR1 to VAR3). Two exemplary prediction simulations that used different annual numbers of load cycles to failure have been performed. The two examples neglected the annual increase of heavy traffic and thus the number of load cycles to failure in order to exclusively concentrate on the influence of climatic conditions on the durability of the asphalt bearing course.

Example 1: The annual numbers of load cycles to failure were defined depending on the three variants of the thermophysical asphalt properties (VAR1 to VAR3) such that the total damage value according to the Miner’s law for the 30-year reference period 1980 to 2009 was always „1“. Thus it becomes possible to identify and estimate differences between the effects of the thermophysical asphalt properties on the fatigue behaviour of the asphalt bearing course and thus on the service life of the asphalt pavement structure on the basis of changes of the climatic ambient conditions.

Example 2: The same annual number of load cycles to failure was defined for all three variants of the thermophysical asphalt properties (VAR1 to VAR3). This number is defined on the basis of the number of cycles to failure of variant VAR2 defined in example 1.

If the design of asphalt pavement structures is done on the basis of the climatic conditions of the last 30 years (period: 1980 - 2009), it is quite probable that the fatigue life of these structures will be significantly shorter as we assume future climate changes according to scenario A1B. Thus for example, the service life of asphalt pavement structure which will be build in the second third of this century, will be approximately 5 to 10 years shorter. From 2050, their fatigue lives will be shorter by even approximately 10 to 15 years (Figure 8 – left). It seems principally possible to counteract the shorter fatigue life due to climate changes by accordingly changing the thermal properties of asphalt. However, this alone will not compensate the trend towards shorter service life (Figure 8). Moreover, the necessity to take account of the individual thermophysical asphalt properties in the design process is obvious. If this is neglected it may happen that asphalt pavement structures, whose service life will begin already in the next five years, may considerably vary regarding the length of their fatigue lives. For the bandwidth of the thermophysical asphalt properties analysed in this research, the service life differences are approximately 20 years (Figure 8 – right). By the end of the total observation period between 1980 and 2069, a decrease of the differences of service life as a result of different thermophysical asphalt properties can be expected.

Nevertheless, the differences will still be 10 years starting in the second third of this century and 5 years starting in the middle of this century.

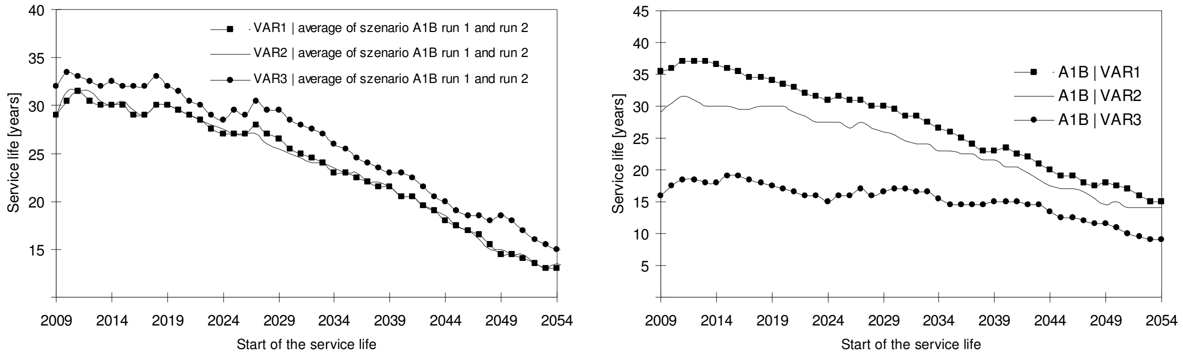


Figure 8: Service life of asphalt pavement structures according to example 1 (left) and according to example 2 (right) depending on the start of the service life and the thermophysical asphalt properties.

The development of service life presented in Figure 8 reflects the future climate changes in the 30-year period of 1980 to 2009 (climatic basis for dimensioning). Even if the climatic basis for design will be adapted on the basis of the climatic conditions of the previous 30 years, it will not be possible to compensate the negative effects of the climate changes, which are predicted in scenario A1B, on the fatigue life of asphalt pavement structures (Figure 9).

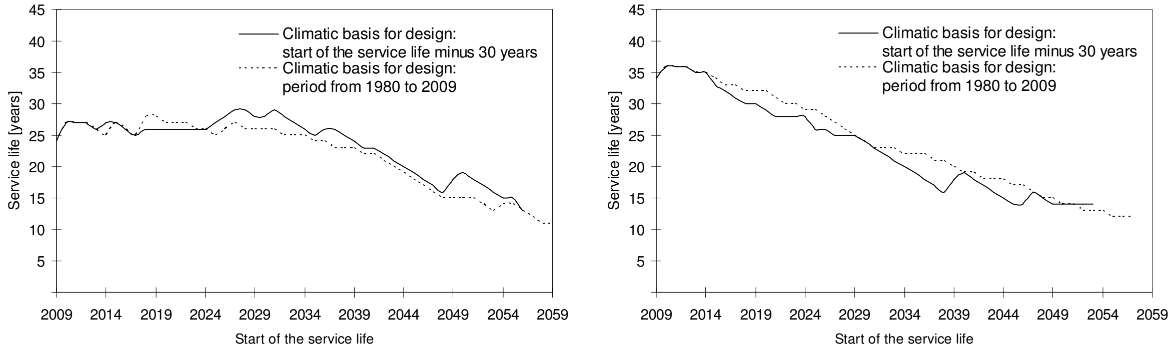


Figure 9: Service life of asphalt pavement structures depending on the start of the service life and the climatic basis for design – VAR2; A1B-1 (left); A1B-2 (right).

7 SUMMARY

It is most likely that climate, which will probably change in the next decades, will also influence the service life of asphalt pavement structures. If we assume the occurrence of emission scenario A1B, it is highly probable that the thermal stresses acting on asphalt pavement structures will drastically increase in some cases. These stress changes are eventually reflected by changing service life of asphalt pavement structures. For the sake of an economically and ecologically sustainable development of road construction, it will be vital to take into account the future climate changes in the design process of asphalt pavement structures. For a responsible and future-oriented management of our resources, it is recommended to act adequately and early, i.e. already today, instead of reacting to the climatic developments only in a couple of years and with much less success.

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