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THE IMPACT OF CLIMATE CHANGE ON PAVEMENT TEMPERATURES AND ASPHALT BINDER GRADE SELECTION IN ESTONIA BASED ON DIFFERENT CLIMATE CHANGE SCENARIOS

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Abstract. This paper examines the impact of climate change on asphalt pavement temperatures and Superpave asphalt binder Performance Grade (PG) selection in Estonia. Pavement temperatures were estimated using statistical-empirical pavement temperature prediction models tailored for Estonian conditions. The impact of climate change on pavement temperatures was assessed based on the latest climate change models, assuming three different climate change scenarios for the near, medium and long terms. Projected changes reflect warming trends, with both coastal and mainland areas experiencing substantial shifts in binder grades. Asphalt binder low temperature PG grades are more significantly influenced by climate change, leading to narrower pavement temperature ranges in the region.

Keywords: asphalt binder, climate change, pavement temperature, performance grading, Superpave.

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Introduction and background

Human activities, particularly the burning of fossil fuels (coal, oil, and natural gas), deforestation, and industrial processes have significantly increased the concentrations of greenhouse gases (such as carbon dioxide, methane, and nitrous oxide) in the atmosphere. These increased concentrations enhance the natural greenhouse effect, leading to global warming and climate change (Krinner et al., 2023; Myers et al., 2015; Ripple et al., 2024).

Rising global temperatures lead to extreme weather events, such as heat waves, which can damage roads, bridges, and buildings (FHWA, 2015; Pörtner et al., 2022). The performance of asphalt pavements is significantly influenced by temperature, with the asphalt binder playing a critical role in the pavement's overall behaviour. Higher air and pavement temperatures, particularly during warmer seasons, can lead to irreversible plastic deformations, such as longitudinal rutting and shoving, especially under heavy and slow-moving traffic (FHWA, 2015). In cold regions such as Northern Europe and North America, low air temperatures cause asphalt to become stiffer and less tolerant to strain, increasing the risk of brittle behaviour and premature pavement cracking. Furthermore, asphalt pavements are susceptible to temperature-induced shrinkage and low-temperature cracking, which further exacerbates the likelihood of premature pavement failure (Hesp et al., 2009; Yee et al., 2006). In the USA alone, the climate change is predicted to add from 13.6 to 35.8 billion US dollars to pavement costs based on different climate projections (Underwood et al., 2017).

1. Pavement temperatures and asphalt binder grade selection

Incorrect asphalt binder grade selection reduces the expected service life of roads, leading to higher maintenance costs for road users and taxpayers (FHWA, 2015; Underwood et al., 2017). Therefore, selecting asphalt binder properties based on local environmental conditions is crucial to ensure the durability and performance of asphalt pavements. In Europe, asphalt binder grade is still decided based on empirical specifications known as penetration grading (CEN, 2009, 2010). However, penetration grading has been criticised for its weak correlation with in-service pavement performance (Adams & Holmgreen, 1986; Kennedy et al., 1994; Petersen et al., 1993). To address these limitations, asphalt binder selection in North America is based on the Superpave (Superior Performing Asphalt Pavements) Performance Grading system, outlined in the AASHTO M 320 specification. According to Superpave principles, asphalt binder grades are denoted as PG HT-LT, where PG stands for Performance Grade, and HT-LT represents the high- and low-temperature grades, respectively. PG grades specify the temperature range, in which the binder is expected to perform adequately under environmental and loading conditions. For example, a binder grade of PG 58-22 indicates suitability for regions where pavement temperatures range from a maximum of +58 °C to a minimum of −22 °C. As per the Superpave specification, PG grades are typically defined in 6 °C increments. (Asphalt Institute, 2011).

The required asphalt binder PG grade for a specific road section is determined using historical air temperature data and predetermined air-pavement temperature relationship models. The pavement's maximum temperature is calculated using Equation (1), and the minimum temperature is calculated using Equation (2). These models were developed based on recorded temperature data from 30 road test sections across North America as part of the Seasonal Monitoring Program under the Long-Term Pavement Performance (LTPP-SMP) study (Asphalt Institute, 2011; Mohseni, 1998).

$$T_{\text{pav,max}} = 54.32 + 0.78 \times T_{\text{air,max}} - 0.0025 \times \text{Lat}^2 - 15.14 \times \text{Log}_{10}(H + 25), \qquad (1)$$

where
$T_{\text{pav,max}}$ – maximum pavement temperature at depth H, °C;
$T_{\text{air,max}}$ – daily maximum air temperature or 7-day average high temperature for Performance Grading purposes, °C;
Lat – latitude of the specific road section, °;
H – depth from pavement surface, mm.

$$T_{\text{pav,min}} = -1.56 + 0.72 \times T_{\text{air,min}} - 0.004 \times \text{Lat}^2 + 6.26 \times \text{Log}_{10}(H + 25), \qquad (2)$$

where
$T_{\text{pav,min}}$ – minimum pavement temperature at depth H, °C;
$T_{\text{air,min}}$ – daily minimum air temperature, °C;
Lat – latitude of the specific road section, °;
H – depth from pavement surface, mm.

Several studies have highlighted that these models may be unsuitable for regions outside the USA. Specifically, they tend to under- or overestimate pavement in-service temperatures at higher latitudes (Kontson et al., 2023, 2024; Swarna et al., 2023). To address this issue, the authors of this publication have developed separate pavement temperature prediction models using air-pavement temperature data collected in Estonia. The maximum pavement temperature for Estonian regions can be estimated using Equation (3), while the minimum pavement temperature can be estimated using Equation (4). Field validation demonstrated that these models reflect pavement in-service temperatures more accurately compared to the LTPP-SMP models (Kontson et al., 2024).

$$T_{\text{pav,max}} = 1.6302 \times T_{\text{air,max}} - 16.8975 \times \text{Log}_{10}(H + 25) + 27.8947, \quad (3)$$

where
$T_{\text{pav,max}}$ – maximum pavement temperature at depth H, °C;
$T_{\text{air,max}}$ – daily maximum air temperature or 7-day average high temperature for Performance Grading purposes, °C;
H – depth from pavement surface, mm.

$$T_{\text{Pav,min}} = 0.6944 \times T_{\text{Air,min}} + 3.4507 \times \text{Log}_{10}(H + 25) - 6.6132, \quad (4)$$

where
$T_{\text{pav,min}}$ – minimum pavement temperature at depth H, °C;
$T_{\text{air,min}}$ – daily minimum air temperature, °C;
H – depth from pavement surface, mm.

2. CMIP6 climate change model and projections

Climate change models are essential tools for scientists to analyse historical climate changes and predict future trends. These models simulate the physical, chemical, and biological processes of the atmosphere, land, and oceans. They are continually refined as research groups worldwide incorporate higher spatial resolutions, new physical processes, and biogeochemical cycles. These updates are typically aligned with the timeline of the Intergovernmental Panel on Climate Change (IPCC) assessment reports, with model outputs released in preparation for each report (Eyring et al., 2016; Krinner et al., 2023).

The latest IPCC Sixth Assessment Report (AR6) utilises data and projections from CMIP6 (Coupled Model Intercomparison Project Phase 6). CMIP6 is the most current and comprehensive set of climate simulations, supporting climate change assessments and projections. These projections are based on scenarios previously referred to as Representative Concentration Pathways (RCPs). However, IPCC AR6 now relies on Shared Socioeconomic Pathway (SSP) scenarios, which have replaced RCPs (Krinner et al., 2023). SSPs provide a more comprehensive framework by incorporating socioeconomic factors such as population growth, economic development, and technological advancements. This approach enhances the understanding of how these factors influence greenhouse gas emissions and climate change, offering a more holistic perspective for climate modelling and policymaking (van Vuuren & Carter, 2014).

There are mainly three SSP scenarios that are typically referred to (Krinner et al., 2023; van Vuuren et al., 2021):

- SSP1-2.6 represents an optimistic scenario where the world achieves rapid technological advancements, transitions to renewable energy, and addresses social and environmental issues, resulting in relatively low levels of climate change (with global warming likely staying below 2 °C by 2100). The "2.6" refers to the level of radiative forcing (measured in watts per square meter) by 2100.
- SSP2-4.5 is considered a "moderate" or "Middle-of-the-Road" scenario for both socioeconomic development and climate change, where emissions continue at a pace that leads to a temperature increase of approximately 2–3 °C by 2100.
- SSP3-7.0 is a high-emissions, low-development pathway characterised by slow economic growth, high inequality, and limited technological progress. It assumes a fragmented world with poor international cooperation, resulting in high emissions and significant climate change impacts. By 2100, this scenario could lead to a global temperature increase of 3.5–4 °C, which would have severe consequences for ecosystems, human health, and infrastructure.

While there is uncertainty about which SSP pathway will ultimately prevail, SSP2-4.5 is often considered the most likely because it reflects a continuation of current global trends: moderate socioeconomic development, gradual technological progress, and emissions reductions that are not aggressive enough to limit global warming to 2 °C or below (Scafetta, 2024).

3. Objectives

The main objective of this study is to assess the impact of different climate change scenarios on pavement temperatures and Superpave PG grading for Estonia. The assessment uses historical temperature data from 2004 to 2024 and evaluates the impact of climate change based on CMIP6 projections for SSP1-2.6, SSP2-4.5, and SSP3-7.0. The results of the analysis are then used to update the Superpave PG grading to better align with Estonian conditions.

4. Geographical location and climate

Estonia is located in Northern Europe, bordering the Baltic Sea and the Gulf of Finland. It shares land borders with Latvia and Russia and maritime borders with Finland and Sweden. The geographical coordinates of Estonia range from

57°30’ N to 59°49’ N and 21°46’ E to 28°13’ E. The climate is characterised by four distinct seasons, influenced by both maritime and continental climatic factors. The annual average air temperature is 6–7 °C. The highest recorded (11 August 1992), and lowest recorded air temperatures (17 January 1940) are 35.6 °C and −43.5 °C, respectively. The warmest months are June–August, and the coldest are December–February (Estonian Environmental Agency, 2021).

5. Methodology

Meteorological data analysis and projected climate change impact on pavement temperatures were divided into two stages:

Stage I – Calculation of pavement temperatures and Superpave PG HT and LT grades was based on historical temperature data from selected weather stations (Figure 1). Air temperature data from 2004 to 2024 was used for both PG HT and PG LT estimations, according to Equations (3) and (4), respectively.

Stage II – Assessment of the impacts of climate change on pavement temperatures was based on selected weather stations, for the near (2025–2044), medium (2045–2064), and long-term (2065–2084) periods. The calculations were based on the Shared Socioeconomic Pathways SSP1-2.6, SSP2-4.5, and SSP3-7.0 scenarios.

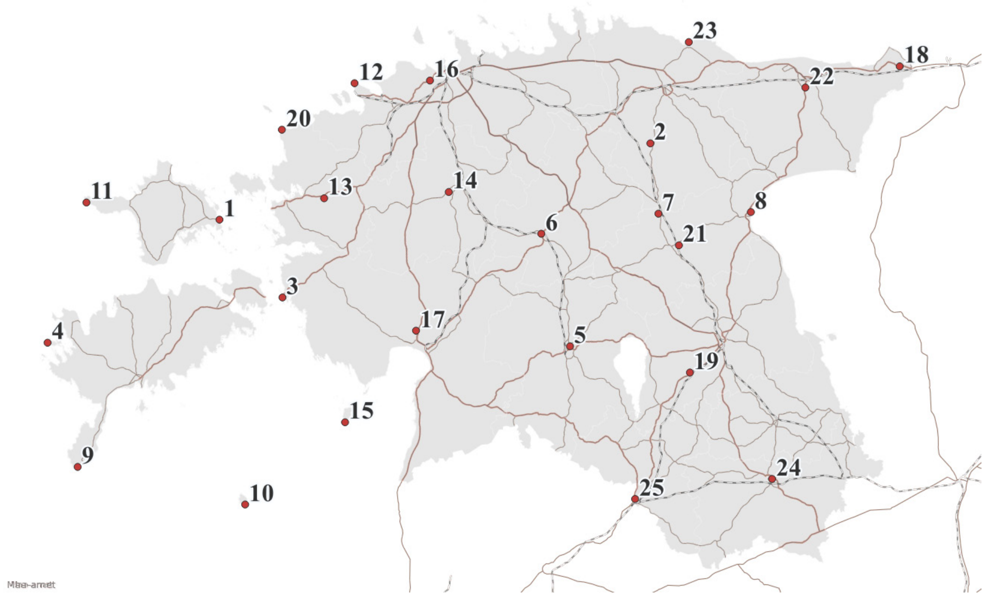

Figure 1. Numbers and locations of the meteorological stations used in the study

Pavement high temperatures are calculated based on historical 1-day average high and 7-day average high air temperatures using Equation (3). The 1-day average high air temperature is used for calculating the maximum pavement temperature. The 7-day average high air temperature is used as the basis for determining PG HT grades for a given station. PG HT grade determination depth is 20 mm (h = 20 mm) from pavement surface. Pavement PG LT grades are calculated based on 1-day average minimum air temperatures using Equation (4). PG LT grade is determined at the surface (h = 0 mm). To achieve at least 98% reliability, the standard deviations (2 × Std dev) of annual 1-day maximum, 7-day maximum, and 1-day minimum air temperatures were also considered in the calculations.

To account for the impacts of climate change in the pavement temperature calculations, changes in the daily maximum temperatures (TXx) for the June–August period and the daily minimum temperatures (TNn) for the December–February period (at 2 m above ground level) relative to the reference period 2004–2024 were extracted from the CMIP6 model. The CMIP6 model average TXx and TNn changes relevant to the Estonian region were derived from the CMIP6 model using the Copernicus Climate Change Service (C3S) online interface, specifically the Copernicus Interactive Climate Atlas. Three 20-year periods were considered for climate change projections: 2025–2044 (near term), 2045–2064 (medium term), and 2065–2084 (long term).

6. Results

The results of the meteorological data analysis for the selected meteorological stations are presented in Table 1. The table also indicates the current PG grades for the locations with reliability ≥98%, based on temperature data from 2004 to 2024. Figures 2 to 4 show the current and estimated changes in pavement maximum surface temperatures due to climate change over the near, medium, and long term. The current PG zone maps are presented in Figure 5.

The calculated pavement temperatures are lowest in coastal areas and on the islands of Western Estonia. In these regions, the highest summer pavement surface temperatures stay below 60 °C, while on the mainland, temperatures are near or slightly above this threshold. The PG HT grade (h = 20 mm), calculated based on the seven consecutive warmest days, is primarily 52 °C for the coastal areas and islands of Western Estonia. According to data from the Sõrve station, the PG HT grade would be 46 °C. On the mainland, the dominant PG HT grade is 58 °C, and in North-East Estonia, it is 52 °C (except for Narva, where the PG HT is 58 °C). Warmer minimum pavement surface temperatures prevail in coastal areas and on the islands of Western Estonia, with the PG LT grade (h = 0 mm) primarily at −22 °C. On the mainland, the dominant PG LT grade is −28 °C, and the lowest PG LT grade is −34 °C, which is observed at two stations located in North-East Estonia (Jõgeva and Jõhvi).

Based on temperature data from 2004 to 2024 and the currently implemented Superpave PG grading determination principles, the primary asphalt binder grades in Estonia would fall within the range of PG HT 52 to 58 °C and PG LT −22 to −34 °C. At present, penetration grade 70/100 is predominantly used across Estonia, which satisfies the required PG HT grades. However, PG LT grade −34 °C is not achievable with this penetration grade, and PG LT grade −28 °C is only achievable with high-quality penetration grade 70/100 binders having low tendency towards physical hardening (Lill et al., 2020a; Lill et al., 2020b). Regions with PG LT −28 and −34 could benefit from using softer binders, e.g., penetration grade 100/150 or 160/220.

Table 1. Average daily maximum and minimum air temperatures and average 7-Day maximum air temperatures with standard deviations (SD) over observed period of 2004 to 2024. PG HT and LT grades are calculated with 98% reliability based on 7-day maximum air temperature and 1-day minimum air temperature data, respectively

(table continues on the next page)

Station no.	Station name	1-Day T_{air} max		7-day T_{air} max		1-day T_{air} min		PG grade	
		T_{air} max °C	Std dev	T_{air} max °C	Std dev	T_{air} min °C	Std dev	HT	LT
1	Heltermaa	28.9	2.1	26.0	2.1	−19.2	5.2	52	−28
2	Väike-Maarja	30.3	1.9	27.3	2.2	−25.2	5.2	52	−28
3	Virtsu	29.5	2.2	26.5	1.9	−20.3	5.3	52	−28
4	Vilsandi	28.6	2.3	25.4	2	−14.5	5	52	−22
5	Viljandi	31.4	1.8	28.4	1.9	−24.1	5.6	58	−28
6	Türi	30.8	1.8	27.9	2.1	−23.8	4.9	58	−28
7	Tooma	30.8	1.8	27.7	2.2	−25.4	5.5	58	−28
8	Tiirikoja	29.6	1.7	26.7	1.6	−24.8	5.9	52	−28
9	Sõrve	26.9	2.0	24.3	1.7	−14.6	4.8	46	−22
10	Ruhnu	27.6	1.8	25.3	1.7	−13.3	4.3	52	−22
11	Ristna	28.5	2.3	25.5	2.2	−15.7	4.6	52	−22
12	Pakri	29.6	2.3	24.8	2.2	−17.5	5.2	52	−22
13	Lääne-Nigula	30.7	1.9	27.8	2.3	−22.7	5.0	58	−28
14	Kuusiku	30.5	1.7	27.8	2.1	−24.8	5.0	58	−28
15	Kihnu	29.2	1.7	26.3	1.9	−17.7	5.2	52	−22
16	Tallinn-Harku	30.4	2.1	27.0	2.5	−20.1	4.6	58	−28
17	Pärnu	30.6	1.5	27.6	1.9	−22.3	6.0	52	−28
18	Narva	31	2.2	27.6	2.3	−23.8	5.2	58	−28
19	Tartu	31.2	1.5	28.0	2.1	−24.6	5.8	58	−28

Table 1. (continue) **Average daily maximum and minimum air temperatures and average 7-Day maximum air temperatures with standard deviations (SD) over observed period of 2004 to 2024. PG HT and LT grades are calculated with 98% reliability based on 7-day maximum air temperature and 1-day minimum air temperature data, respectively**

Station no.	Station name	1-Day T_{air} max		7-day T_{air} max		1-day T_{air} min		PG grade	
		T_{air} max °C	Std dev	T_{air} max °C	Std dev	T_{air} min °C	Std dev	HT	LT
21	Jõgeva	31	1.8	27.9	2.1	–26.9	5.5	58	–34
22	Jõhvi	30.2	2.2	27.2	2.3	–25.9	6.0	52	–34
23	Kunda	30.7	2.6	26.6	2.6	–21.2	5.8	52	–28
24	Võru	31.7	1.6	28.6	1.9	–25.4	5.7	58	–28
25	Valga	31.4	1.6	28.4	1.9	–24.9	5.7	58	–28

Near-term climate change is expected to affect pavement maximum surface temperatures by approximately 1–2 °C, depending on the selected SSP scenario. The SSP1-2.6 scenario leads to an increase in surface temperatures by 0–1 °C, while SSP2-4.5 and SSP3-7.0 result in a 1–2 °C increase in pavement maximum surface temperatures. In the medium term, pavement maximum surface temperatures are projected to increase by 1–2 °C, 2–3 °C, and 3–4 °C under the SSP1-2.6, SSP2-4.5, and SSP3-7.0 scenarios, respectively. In the long term, pavement maximum surface temperatures are projected to increase by 1–2 °C, 3–4 °C, and 4–5 °C under the SSP1-2.6, SSP2-4.5, and SSP3-7.0 scenarios, respectively.

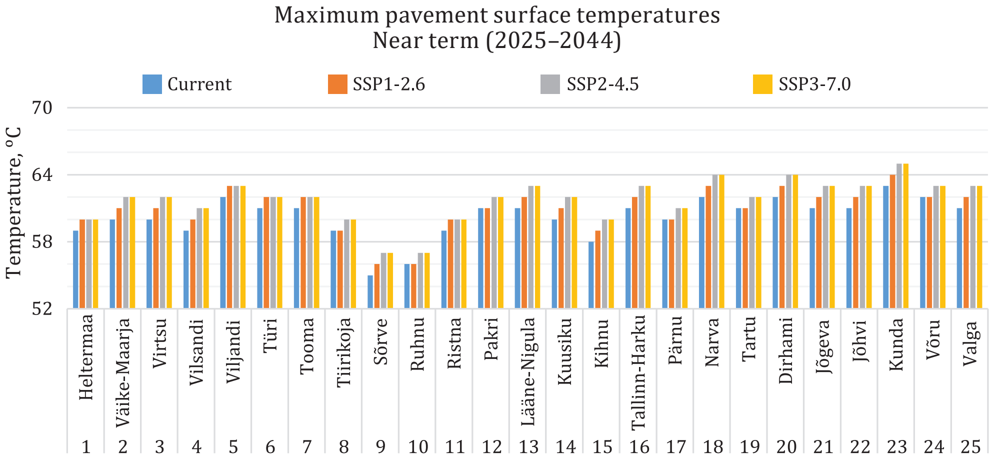

Figure 2. Estimated near-term pavement maximum surface temperatures based on average 1-day maximum air temperatures from 2004 to 2024 (with ≥ 98% reliability)

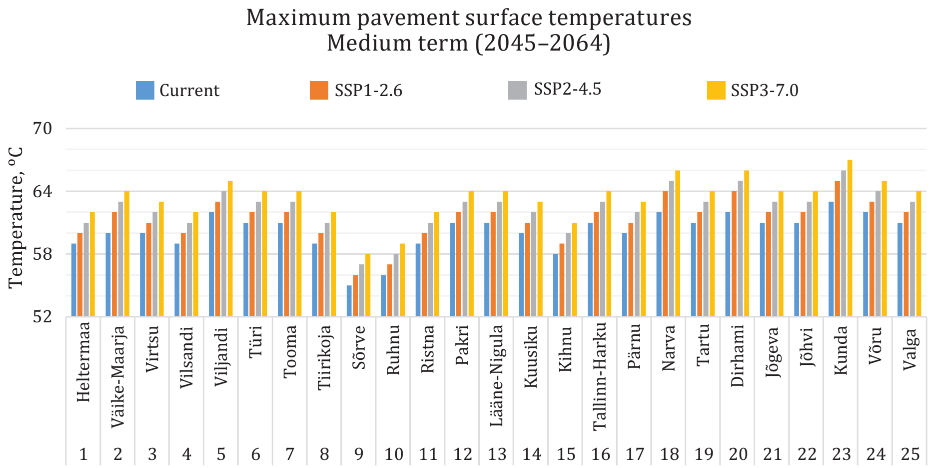

Figure 3. Estimated medium-term pavement maximum surface temperatures based on average 1-day maximum air temperatures from 2004 to 2024 (with ≥ 98% reliability)

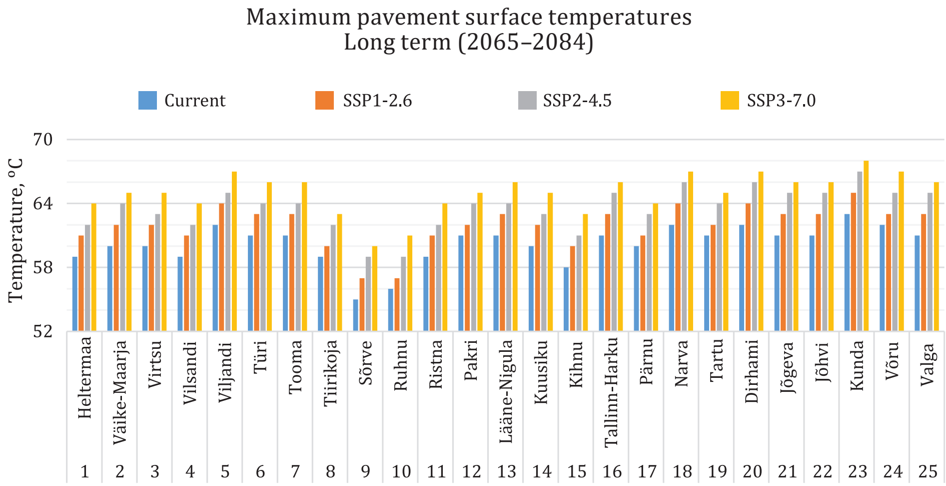

Figure 4. Estimated long-term pavement maximum surface temperatures based on average 1-day maximum air temperatures from 2004 to 2024 (with ≥ 98% reliability)

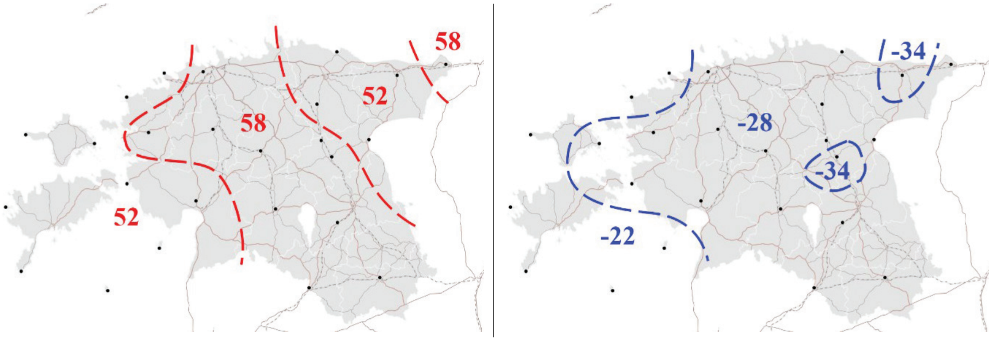

Figure 5. Calculated pavement PG HT and LT design temperatures based on air temperature data from 2004 to 2024

The impact of climate change on Superpave PG grades was assessed based on changes in pavement PG HT and LT temperatures. Calculations for PG HT and LT temperatures were made using 7-day maximum air temperature and 1-day minimum air temperature data, including the standard deviations described in Table 2. The calculated PG HT results are shown in Figures 6 to 8, while the PG LT results are presented in Figures 9 to 11. All results are rounded to the nearest whole number. Changes in PG HT and LT grades for each station are outlined in Table 2. Figures 12 to 14 depict the PG zones for the near to long term based on SSP2-4.5 scenarios.

6.1. Near-term scenarios (2025–2044)

In the near-term SSP1-2.6 scenario, the PG HT grade increases in three locations (Väike-Maarja, Jõhvi, Kunda from 52 to 58 °C). In the same scenario, the PG LT grade increases in four locations (Heltermaa, Tallinn-Harku from −28 to −22 °C; Jõgeva, Jõhvi from −34 to −28 °C). In near-term SSP2-4.5 and SSP3-7.0 scenarios, the PG HT grade increases in five locations (Väike-Maarja, Pärnu, Jõhvi, Kunda from 52 to 58 °C; Sõrve from 46 to 52 °C). In the same scenarios, the PG LT grade increases in six locations (Heltermaa, Virtsu, Tallinn-Harku from −28 to −22 °C; Ruhnu from −22 to −16 °C; Jõgeva, Jõhvi from −34 to −28 °C).

6.2. Medium-term scenarios (2045–2064)

In the medium-term SSP1-2.6 and SSP2-4.5 scenarios, the PG HT grade increases in the same five locations (Väike-Maarja, Jõhvi, Kunda, Pärnu from 52 to 58 °C; Sõrve from 46 to 52 °C). In SSP1-2.6 scenario, PG LT increases in five locations (Heltermaa, Virtsu, Tallinn-Harku from −28 to −22 °C; Jõgeva, Jõhvi from −34 to −28 °C). However, in SSP2-4.5 scenario, the number of locations where PG LT increases is 12 (Heltermaa, Virtsu, Türi, Lääne-Nigula, Tallinn-Harku, Kunda from −28 to −22 °C; Jõgeva, Jõhvi from −34 to −28 °C; Vilsandi, Sõrve, Ruhnu, Ristna,from from −22 to −16 °C). In SSP3-7.0 scenario, the PG HT grade increases in eight locations (Heltermaa, Väike-Maarja, Virtsu, Kihnu, Pärnu, Jõhvi, Kunda from 52 to 58 °C; Sõrve from 46 to 52 °C) and PG LT grade increases in 17 locations (Heltermaa, Väike-Maarja, Virtsu, Viljandi, Türi, Lääne-Nigula, Kuusiku, Tallinn-Harku, Pärnu, Narva, Kunda from −28 to −22 °C; Vilsandi, Sõrve, Ruhnu, Ristna from −22 to −16 °C; Jõgeva, Jõhvi from −34 to −28 °C).

6.3. Long-term scenarios (2065–2084)

In the long-term SSP1-2.6 scenario, the PG HT grade is increasing in the same five locations as described for medium term SSP1-2.6 scenario, but PG LT grade would increase 15 locations (Heltermaa, Virtsu, Türi, Lääne-Nigula, Kuusiku, Tallinn-Harku, Pärnu, Narva, Kunda from −28 to −22 °C; Vilsandi, Sõrve, Ruhnu, Ristna from −22 to −16 °C; Jõgeva, Jõhvi −34 to −28 °C). In SSP2-4.5 scenario, the PG HT grade increases in 10 locations (Heltermaa, Väike-Maarja, Virtsu Tiirikoja, Ristna, Kihnu, Pärnu, Jõhvi, Kunda from 52 to 58 °C; Sõrve from 46 to 52 °C. PG LT grade increases in 22 locations with only three locations remaining unchanged (Kihnu, Dirhami, Võru). In SSP3-7.0 scenario, the PG HT increases in 13 locations (Heltermaa, Väike-Maarja, Virtsu, Vilsandi, Tiirikoja, Ristna, Pakri, Kihnu, Pärnu, Dirhami, Jõhvi, Kunda from 52 to 58 °C; Sõrve from 46 to 52 °C). PG LT increases in all locations. In four locations, the PG LT increases by two grades (Heltermaa, Tallinn-Harku from −28 to −16 °C; Jõgeva, Jõhvi from −34 to −22 °C).

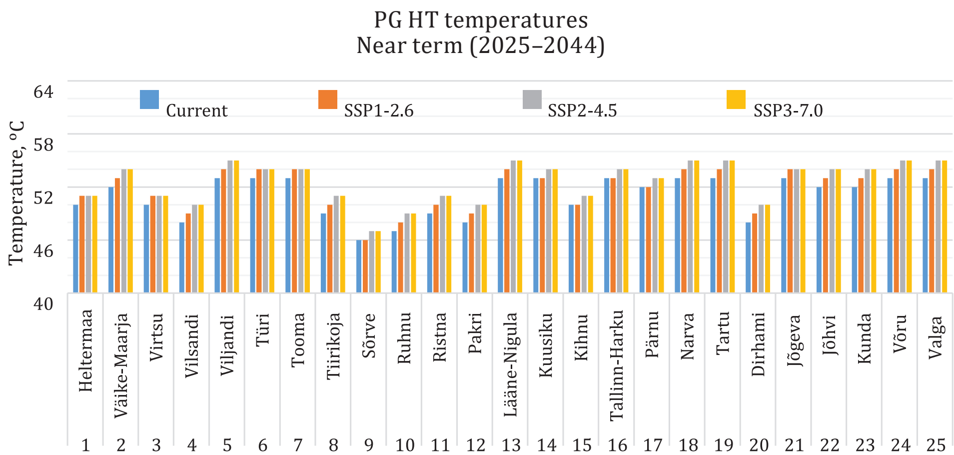

Figure 6. Pavement PG HT true grade temperatures at 20 mm depth under different near-term SSP scenarios (2025–2044)

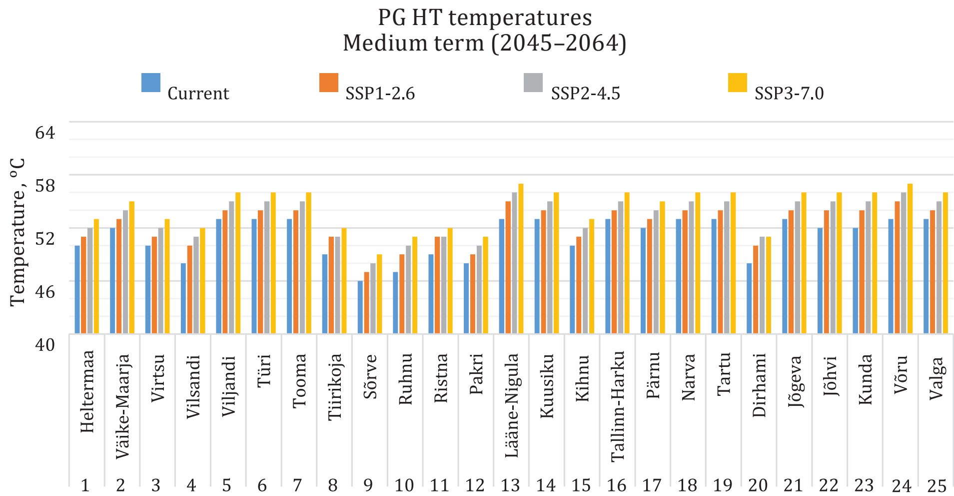

Figure 7. Pavement PG HT true grade at 20 mm depth under different medium-term SSP scenarios (2045–2064)

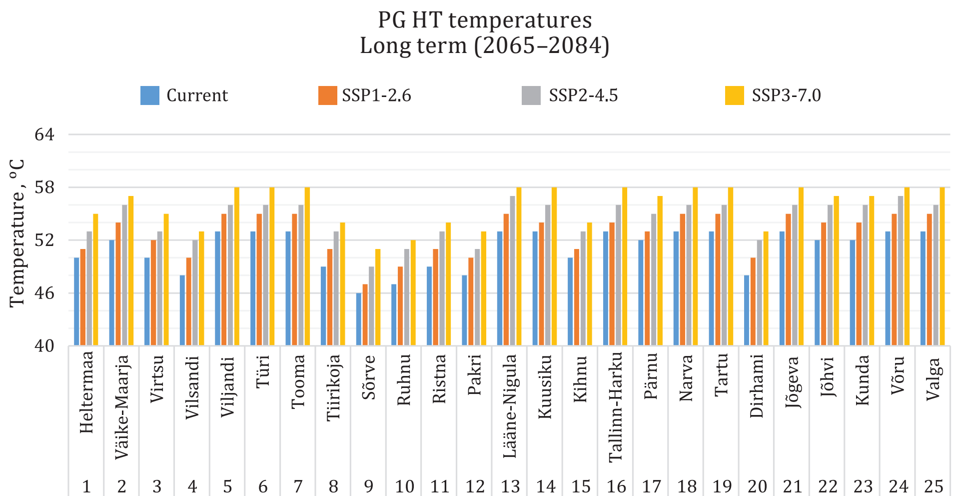

Figure 8. Pavement PG HT true grade at 20 mm depth under different long-term SSP scenarios (2065–2084)

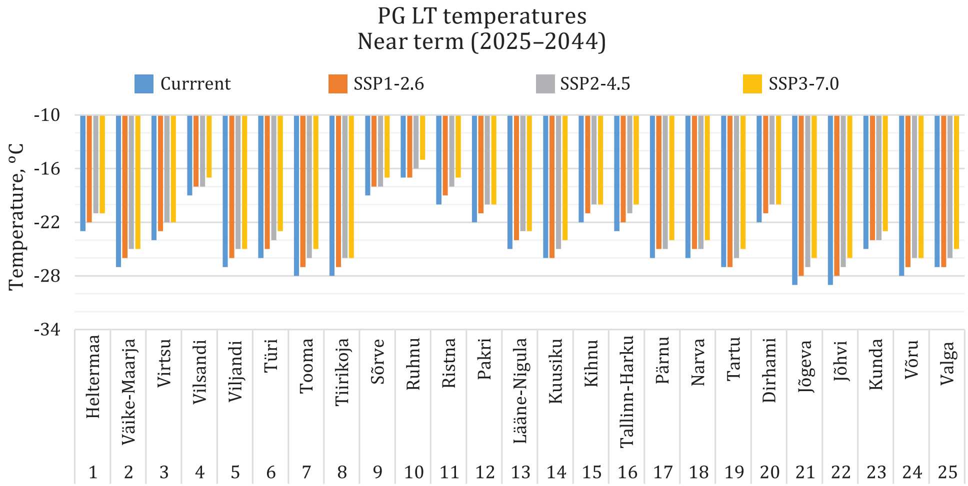

Figure 9. PG LT true grade under different near-term SSP scenarios (2025–2044)

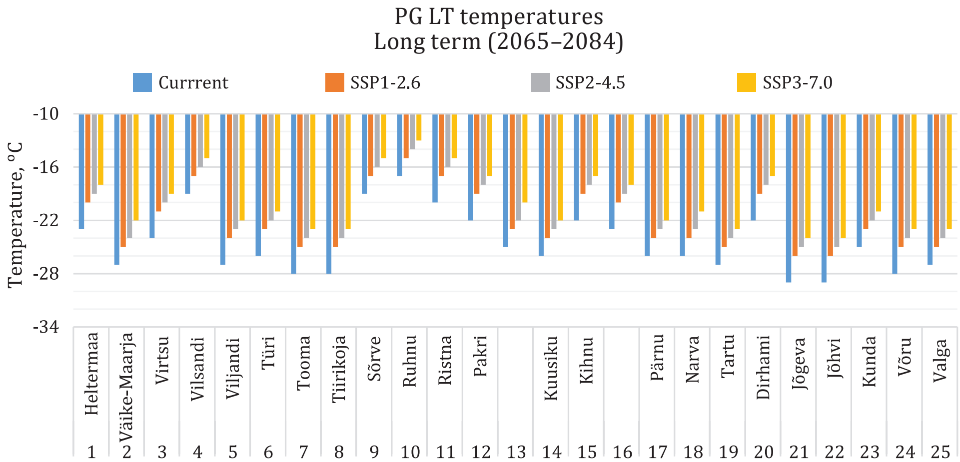

Figure 10. Pavement PG LT true grade under different medium-term SSP scenarios (2045–2064)

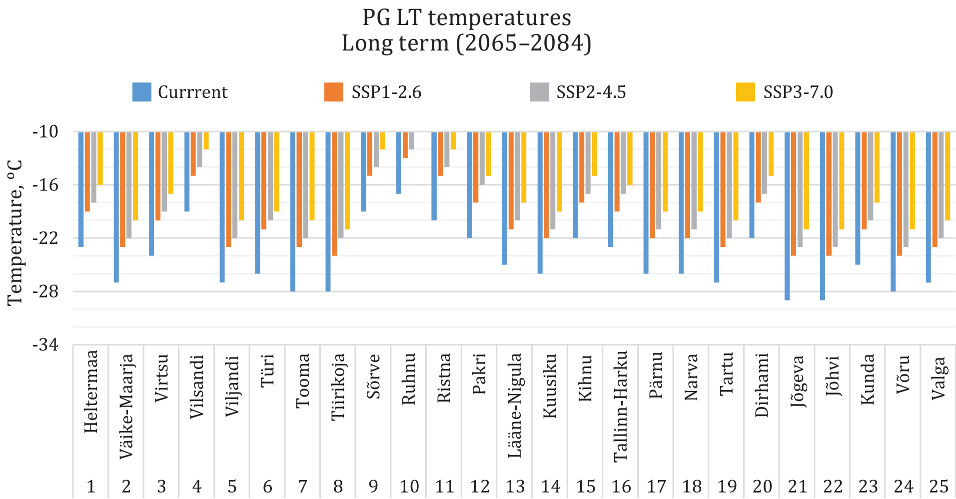

Figure 11. Pavement PG LT true grade under different long-term SSP scenarios (2065–2084)

Table 2. Shift in PG HT and LT Temperatures in different near- (N), Medium- (M) and Long- (L) Term SSP scenarios. One and two plus signs indicate an increase in PG HT and LT grade by one grade (6 °C) or two grades (12 °C), respectively (table continues on the next page)

Station nr	Station	PG HT grade increase									PG LT grade increase								
		SSP1-2.6			SSP2-4.5			SSP3-7.0			SSP1-2.6			SSP2-4.5			SSP3-7.0		
		N	M	L	N	M	L	N	M	L	N	M	L	N	M	L	N	M	L
1	Heltermaa						+		+	+	+	+	+	+	+	+	+	+	++
2	Väike-Maarja	+	+	+	+	+	+	+	+	+						+		+	+
3	Virtsu						+		+	+		+	+	+	+	+	+	+	+
4	Vilsandi									+			+		+	+		+	+
5	Viljandi															+		+	+
6	Türi												+		+	+		+	+
7	Tooma															+			+
8	Tiirikoja						+			+						+			+
9	Sõrve		+	+	+	+	+	+	+	+			+		+	+		+	+
10	Ruhnu												+	+	+	+	+	+	+
11	Ristna						+			+			+		+	+		+	+

Table 2. (continue) **Shift in PG HT and LT Temperatures in different near- (N), Medium- (M) and Long- (L) Term SSP scenarios. One and two plus signs indicate an increase in PG HT and LT grade by one grade (6 °C) or two grades (12 °C), respectively**

Station nr	Station	PG HT grade increase									PG LT grade increase								
		SSP1-2.6			SSP2-4.5			SSP3-7.0			SSP1-2.6			SSP2-4.5			SSP3-7.0		
		N	M	L	N	M	L	N	M	L	N	M	L	N	M	L	N	M	L
14	Kuusiku												+			+		+	+
15	Kihnu						+		+	+									+
16	Tallinn-Harku										+	+	+	+	+	+	+	+	++
17	Pärnu		+	+	+	+	+	+	+	+			+			+		+	+
18	Narva												+			+		+	+
19	Tartu															+			+
20	Dirhami									+									+
21	Jõgeva										+	+	+	+	+	+	+	+	++
22	Jõhvi	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	++
23	Kunda	+	+	+	+	+	+	+	+	+			+		+	+		+	+
24	Võru																		+
25	Valga															+			+

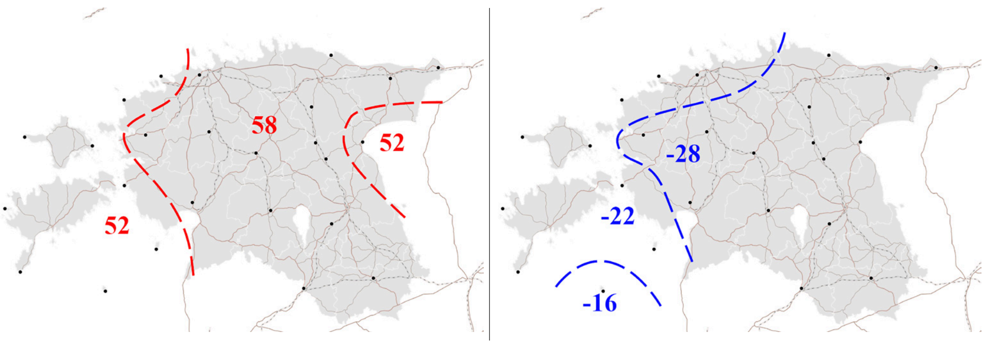

Figure 12. Predicted pavement PG HT and LT design temperatures in 2025–2044 (near term) based on SSP2-4.5

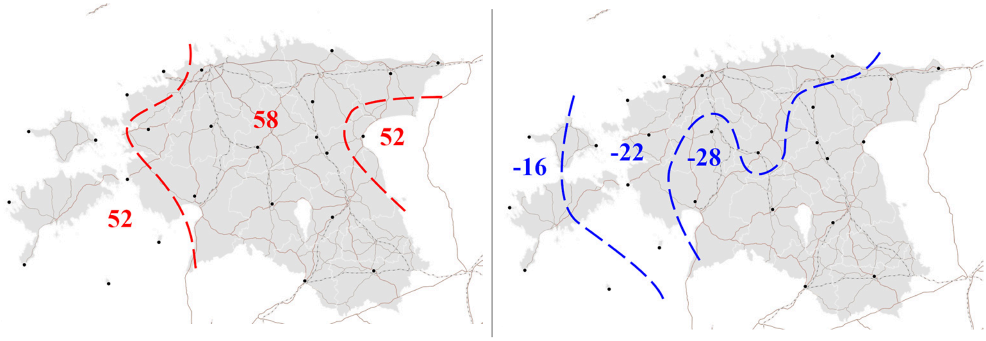

Figure 13. Predicted pavement PG HT and LT design temperatures in 2045–2064 (medium term) based on SSP2-4.5

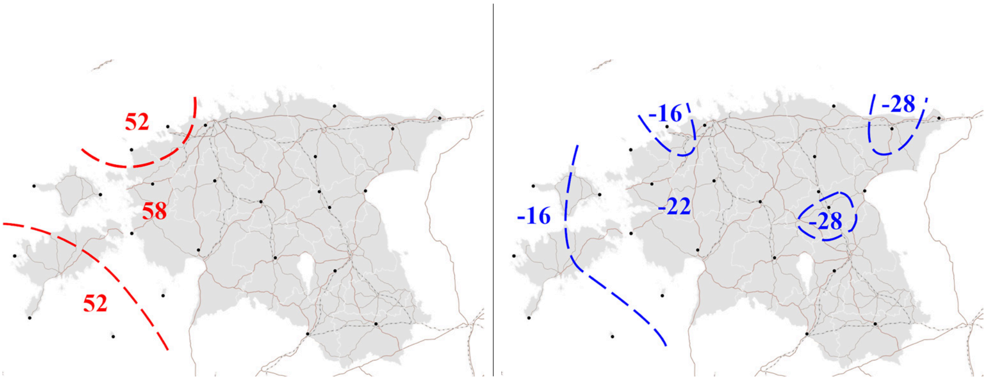

Figure 14. Predicted pavement PG HT and LT design temperatures in 2065–2084 (long term) based on SSP2-4.5

Conclusions

This paper examines the impact of climate change on asphalt pavement temperatures in Estonia. Pavement temperatures were estimated using statistical-empirical pavement temperature prediction models tailored for Estonian climatic conditions. The impact of climate change on pavement temperatures was assessed based on CMIP6 data for the Estonian region, assuming three Shared Socioeconomic Pathway (SSP) scenarios for the near-, medium- and long-terms. Based on the analysed data, the following conclusions can be drawn:

- Pavement temperature analysis reveals regional variations across Estonia, influenced by geographic location. Coastal areas and the islands exhibit the lowest maximum pavement temperatures, while mainland exhibiting the highest pavement maximum temperatures. Based on historical air temperatures from

2004 to 2024, which corresponds to current PG grade determination practice, the PG HT grades for coastal and island regions are 52 °C, dropping to 46 °C at Sõrve. On the mainland, the prevalent PG HT grade is 58° C, with North-East Estonia primarily at 52 °C. Warmer Superpave PG LT temperatures are noted in coastal and island regions, where the PG LT grade is primarily −22 °C. On the mainland, the dominant PG LT grade is −28 °C, with the lowest recorded grade of −34 °C near Jõgeva and Jõhvi in North-East Estonia. Currently, widely used penetration grade 70/100 binders in Estonia are suitable to meet required PG HT grades. However, only high quality 70/100 binders would cover PG LT −28 °C. Regions with PG LT −28 or −34 °C benefit from using softer binders to mitigate risks associated with low temperature cracking.

- All projected climate change scenarios indicate a general increase in both PG HT and LT grades across Estonia. These changes reflect warming trends, with both coastal and mainland areas experiencing substantial shifts in PG HT and LT grades. The LT grades are more significantly influenced by climate change, leading to narrower pavement temperature ranges in the region.
- Under the most likely climate change scenario SSP2-4.5, the PG HT grade is expected to be mostly 58 °C in the observed short-, medium- and long-term perspectives. For PG LT, the dominant grades in the short and medium-term will be −28 and −22 to −28 °C, respectively. In the long-term perspective, PG LT −22 °C will become the most dominant grade. The referenced changes illustrate that due to climate change, the requirements for asphalt binder properties and performance at low temperatures will become less stringent. Conversely, greater consideration must be given to the properties of the binder at high pavement temperatures.

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REFERENCES

Adams, C. K., & Holmgreen, R. J. (1986). *Asphalt properties and pavement performance*. Texas A&M University.

Asphalt Institute. (2011). *The asphalt binder handbook.* Manual series No. 26 (MS-26).

CEN. (2009). *EN 12591:2009. Bitumen and bituminous binders – Specifications for paving grade bitumens*.

CEN. (2010). *EN 14023:2010. Bitumen and bituminous binders – Framework specification for polymer modified bitumens*.

Estonian Environmental Agency. (2021). *Eesti Meteoroloogia Aastaraamat* (in Estonian).

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., & Taylor, K. E. (2016). Overview of the coupled model intercomparison project Phase 6 (CMIP6) experimental design and organization. *Geoscientific Model Development*, *9*(5), 1937–1958. https://doi.org/10.5194/gmd-9-1937-2016

FHWA. (2015). *Climate change adaptation for pavements,* FHWA-HIF-15-015.

Hesp, S. A. M., Soleimani, A., Subramani, S., Phillips, T., Smith, D., Marks, P., & Tam, K. K. (2009). Asphalt pavement cracking: Analysis of extraordinary life cycle variability in eastern and northeastern Ontario. *International Journal of Pavement Engineering*, *10*(3), 209–227. https://doi.org/10.1080/10298430802343169

Kennedy, T. W., Huber, G. A., Harrigan, E. T., Cominsky, R. J., Hughes, C. S., Quintus, H. V., & Moulthrop, J. S. (1994). *Superior performing asphalt pavements (Superpave): The product of the SHRP asphalt research program*. Strategic Highway Research Program, National Research Council.

Kontson, K., Lill, K., & Aavik, A. (2023). Superpave pavement design temperatures in Estonia. *Baltic Journal of Road and Bridge Engineering*, *18*(2), 190–204. https://doi.org/10.7250/bjrbe.2023-18.603

Kontson, K., Lill, K., & Aavik, A. (2024). Statistical-empirical pavement temperature prediction models based on data from road weather stations in Estonia. In *Road Materials and Pavement Design*. Taylor and Francis Ltd. https://doi.org/10.1080/14680629.2024.2415347

Krinner, G. et al. (2023). *Climate Change 2023: Synthesis Report, Summary for Policymakers*. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland. https://doi.org/10.59327/IPCC/AR6-9789291691647.001

Lill, K., Khan, A. N., Kontson, K., & Hesp, S. A. M. (2020a). Comparison of performance-based specification properties for asphalt binders sourced from around the world. *Construction and Building Materials*, *261*, Article 120552. https://doi.org/10.1016/j.conbuildmat.2020.120552

Lill, K., Kontson, K., Khan, A., & Hesp, S. A. M. (2020b). Comparison of physical and oxidative aging tendencies for Canadian and Northern European asphalt binders. *64th Canadian Technical Asphalt Association Annual Conference*. https://www.ctaa.ca/download/abstracts-2019/Abstract-2019-020-Lill.pdf

Mohseni, A. (1998). *LTPP seasonal asphalt concrete (AC) pavement temperature models*. https://rosap.ntl.bts.gov/view/dot/40378

Myers, T. A., Maibach, E., Peters, E., & Leiserowitz, A. (2015). Simple messages help set the record straight about scientific agreement on human-caused climate change: The results of two experiments. *PLOS ONE*, *10*(3), Article e0120985. https://doi.org/10.1371/journal.pone.0120985

Petersen, J. C., Robertson, R. E., Branthaver, J. F., Harnsberger, P. M., Duvall, J. J., Kim, S. S., Anderson, D. A., Christiansen, D. W., & Bahia, H. U. (1993). *Binder characterization and evaluation, Volume 1*. Strategic Highway Research Program, National Research Council.

Pörtner, H.-O., Roberts, D. C., Tignor, M., Poloczanska, E. S., Mitnenbeck, K., Alegria, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., Okem, A., & Rama, B. (2022). *IPCC, 2022: Climate change 2022: Impacts, adaptation and vulnerability.* Cambridge University Press. https://doi.org/10.1017/9781009325844

Ripple, W. J., Wolf, C., Gregg, J. W., Rockström, J., Mann, M. E., Oreskes, N., Lenton, T. M., Rahmstorf, S., Newsome, T. M., Xu, C., Svenning, J.-C., Pereira, C. C., Law, B. E., & Crowther, T. W. (2024). The 2024 state of the climate report: Perilous times on planet Earth. *BioScience*, *74*(12), 812–824. https://doi.org/10.1093/biosci/biae087

Scafetta, N. (2024). Impacts and risks of "realistic" global warming projections for the 21st century. *Geoscience Frontiers*, *15*(2), Article 101774. https://doi.org/10.1016/j.gsf.2023.101774

Swarna, S. T., Hossain, K., & Bernier, A. (2023). Pavement temperature model for Canadian asphalt binder selection: Introduction to the CPT model. *Road Materials and Pavement Design*, *24*(3), 776–794. https://doi.org/10.1080/14680629.2022.2044892

Underwood, B. S., Guido, Z., Gudipudi, P., & Feinberg, Y. (2017). Increased costs to US pavement infrastructure from future temperature rise. *Nature Climate Change*, *7*(10), 704–707. https://doi.org/10.1038/nclimate3390

van Vuuren, D. P., & Carter, T. R. (2014). Climate and socio-economic scenarios for climate change research and assessment: reconciling the new with the old. *Climatic Change*, *122*(3), 415–429. https://doi.org/10.1007/s10584-013-0974-2

van Vuuren, D. et al. (2021). *The 2021 SSP scenarios of the IMAGE 3.2 model*, EarthArXiv. https://doi.org/10.31223/X5CG92

Yee, P., Aida, B., Hesp, S. A. M., Marks, P., & Tam, K. K. (2006). Analysis of premature low-temperature cracking in three Ontario, Canada, pavements. *Transportation Research Record*, *1962*(1), 44–51. https://doi.org/10.3141/1962-06