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Impact of climate change on carbon emissions in future road design: frost protection of roads in temperate climates

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Abstract

The aim of this case study was to estimate the impact of future adaptation to climate change with respect to frost on emissions from road construction. Based on the Representative Concentration Pathways (RCPs) published by the Intergovernmental Panel for Climate Change, the Norwegian Centre for Climate Services has predicted statistical frost quantities for the years 2071–2100 in Norway. Carbon emissions in production, loading, transportation, and construction related to the frost protection of roads were estimated based on the predictions and compared with frost protection based on frost quantities for the years 1981–2010. The case study covered two recently constructed four-lane highways in Norway that represent areas with minor and major frost quantities. Three alternative power sources for machinery and transportation were studied: fossil fuel, biofuel, and electricity. These alternatives were combined with two scenarios for climate change (RCPs): one intermediate (RCP4.5) and one business-as-usual scenario (RCP8.5). Based on the combined alternatives and RCPs, the estimated reduction in CO_2-equivalents ranged from 22% to 90%.

1. Introduction

The global climate is changing owing to human influence, with an average combined land and ocean temperature warming of 0.85 °C over the period 1880–2012 (IPCC 2014). In Norway, the mean annual temperature has increased by 1 °C in the period 1900–2014 (Hanssen-Bauer *et al* 2017).

The Intergovernmental Panel for Climate Change (IPCC) publish reports with Representative Concentration Pathways (RCPs), which describes the pathways of greenhouse gas (GHG) emissions and atmospheric considerations, air pollutant emissions, and land use, based on population size, economic activity, lifestyle, energy use, land use patterns, technology, and climate policy (IPCC 2014). In the IPCC's Fifth Assessment Report (AR5), four 21st century RCPs are presented. RCP2.6 represents the 2 °C goal, relative to the pre-industrial temperatures, whereas RCP4.5 and RCP6.0 are intermediate scenarios, and RCP8.5 represents the 'business as usual' scenario (IPCC 2014, Hanssen-Bauer *et al* 2017). The IPCC published the sixth assessment report (AR6) in March 2023 (IPCC 2023). The meteorological models used for future climate scenarios in this study were based on AR5, as future frost quantities based on AR6 have not yet been calculated for Norway.

The Paris Agreement emphasises the deep concern and urgent requirement of limiting the temperature increase to 1.5 °C above the preindustrial level, recognising that a significant decrease in global emissions is required (UNFCCC 2016). Based on RCP4.5 and RCP8.5, the Norwegian Centre for Climate Services (NCCS) have projected climate change in Norway through the 21st century (Tajet *et al* 2018). The projections indicate an increase in the annual mean temperature from the reference period of 1971–2000–2071–2100. The average increases for the different regions of Norway are 2.7 °C and 4.5 °C

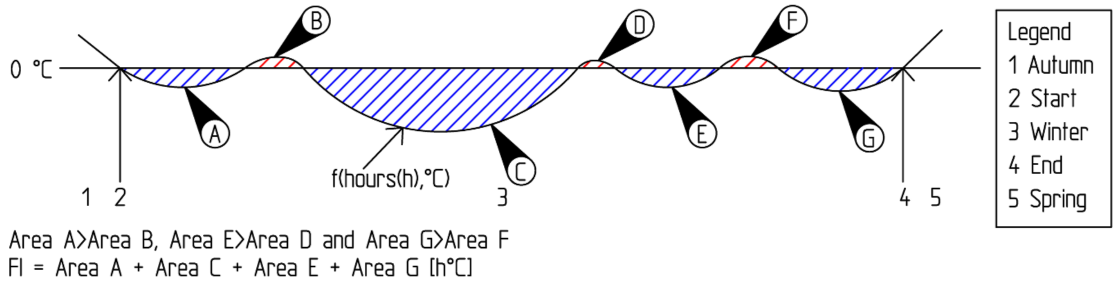

Figure 1. Example of the freezing season accumulation.

under RCP4.5 and RCP8.5, respectively. The projections and results published by the IPCC are mostly based on the Coupled Model Intercomparison Project Phases 5 and 3 (CMIP5 and CMIP3) (IPCC 2013).

CMIP5 consists of 35 climate models (World Climate Research Programme 2021), and the interpretation and comparison in the fifth IPCC report estimate a 99%–100% probability of reduced frequency in the occurrence of cold temperature extremes (IPCC 2014). This is in agreement with a study of data from 12 Norwegian weather stations covering mainland Norway from north to south for the period 1955–2014, indicating a general tendency for a higher increase in minimum temperature compared with the mean temperature and an even larger increase in the lowest seasonal minimum temperature (Førland *et al* 2016).

The frost protection requirements are based on the freezing index (FI) at the geographical location of the project, combined with empirical tables and charts (Norwegian Public Roads Administration 2021c). The FI is calculated based on the mean daily temperature throughout a specific freezing season. For each occurrence of mean daily temperature below 0 °C, the quantity and duration of freezing is calculated as hour-Celsius-degrees (h °C). This can also be expressed in day-Celsius-degrees (d °C). During the freezing season, the occurrence of temperatures above 0 °C is calculated similarly, with the quantity and duration of thawing expressed in h °C. The FI is calculated as the accumulated freezing h °C (areas A, C, E and G in figure 1) minus the accumulated thawing h °C (areas B, D and F) throughout the freezing season (NS-EN ISO 13793:2001 2001). The freezing season begins when the accumulated freezing is greater than the accumulated thawing (point 1 in figure 1) and ends at the maximum FI (point 4 in figure 1).

The statistical principle of return periods and Gumbel distribution is applied to define the design criteria based on the FI. The criterion is denoted by F_x, where x represents the statistical return period (in years) with one occurrence of a frost index at a given quantity (h °C) (NS-EN ISO 13793:2001 2001). Based on the annual average daily traffic (AADT), number of lanes, frost susceptibility of the natural subgrade, and type of structure (rigid or flexible pavement), the frost design criterion is F_{10} or F_{100} based on the design guide published by the Norwegian Public Roads Administration (NPRA). For roads with four or more lanes and an AADT > 8000, F_{100} is used as the frost design criterion. For roads with an AADT of 1501–8000, F_{10} is used as the frost design criterion. For roads with an AADT < 1500, the design for frost protection is limited to an evaluation of risk for uneven frost heave, and typically, there is no frost protection layer.

The frost depth is found using empirical charts, based on the frost quantity F_X at the geographical location of the road, annual mean temperature, and moisture content in the subgrade and the unbound pavement layers. Moisture content is provided by empirical tables based on drainage solution and gradation of the material used in the frost protection layer of the road structure. The depth of the frost protection layer is given by the calculated frost depth to avoid frost penetration into the natural frost-susceptible subgrade. The maximum pavement design depth of flexible road structures with an AADT $\leqslant 8000$ is 1.8 m, whereas roads with an AADT > 8000 have a maximum depth of 2.4 m.

Frost penetration into the frost-susceptible subgrade causes freezing and formation of ice-lenses in the material. In the following thawing period there will be a reduction in the road bearing capacity (Beskow 1947). Furthermore, variations in frost-susceptibility along the road alignment may cause uneven frost heave, which reduces the comfort of road users. Large uneven frost heaves were registered on new Norwegian highways during the winter seasons 2009/2010 and 2010/2011 (Aksnes *et al* 2013). Following these winter seasons, all frost-related requirements for Norwegian public roads were evaluated and updated.

Under a warmer climate and reduced frost penetration, less frost-protection material is required. This adaptation introduces a potential reduction in GHG emissions, air pollutant emissions and land use through reduced production, transportation, and road construction depth. In Norway, the average transportation distance of aggregates from producer to customer is 17.4 km (Norwegian Directorate of Mining 2020), and the energy consumption in transportation of natural gravel, crushed rock, and sand used in road construction is greater than that in production (Rise *et al* 2019). The emissions from the transportation of these materials by trucks were 0.11 million tonnes CO_2 in 2019, which corresponded to 0.2% of Norway's total CO_2 emissions that year (Norwegian Directorate of Mining 2020). The total CO_2 emission of all construction sites has been estimated to 1.2% of the Norwegian annual CO_2 emissions, with a 95% share from transport and machinery (Wiik *et al* 2020). These estimates of transportation and CO_2 emissions related to aggregates used in road construction also include aggregates in other layers. However, the potential reduction in GHG emissions is considerable with the continued improvement in the Norwegian road network.

In the National Transport Plan of Norway 2022–2033, projects with four-lane roads amount to 810 km of road, with 125 km of these already under construction and 224 km of road prioritised for the first six years (Norwegian Ministry of Transport 2020). Reducing the carbon footprint in the construction industry has been and will be a significant part of attaining national climate goals. The goals of Norway are to reduce emissions by 50%–55% by 2030 and 90%–95% by 2050 relative to 1990 levels. A reduction of 90%–95% corresponds to a further reduction of 45–48 million tonnes CO_2-equivalent from 2019 (Norwegian Ministry of Climate and Environment 2021).

Three research questions were addressed to form the basis of estimating the impact of climate change on carbon emissions from frost protection in future road construction:

(1) What are the changes in frost quantities in the statistical period 2071–2100 based on RCP4.5 and RCP8.5 compared with frost quantities in the statistical period 1971–2000?
(2) With the current (2022) design criteria for Norwegian high-volume four-lane roads, what is the difference in the required volume of the frost protection layer in 2071–2100 based on RCP4.5 and RCP8.5 compared with frost quantities in the statistical period 1981–2010?
(3) Based on the calculated differences in the volumes of the frost protection layer and development in machinery, what changes can be estimated in emissions in kg CO_2-equivalent related to frost protection?

All research questions were approached within a Norwegian context with regard to climate change scenarios, machinery, emission factors, and specific design criteria. However, the results may also be applicable to other countries with cold winters.

Research Question 2 was approached using frost quantities in 2022 based on the statistical period 1981–2010 and frost quantities projected for the period 2071–2100. Note that the statistical period was not 1971–2000 as in Research Question 1 because the design criteria in 2022 following Norwegian road design was based on the statistical period 1981–2010. The average difference in F_{100} of all Norwegian municipalities based on the statistical periods 1971–2000 and 1981–2010 is 12 h °C, which is negligible. Pavements have been designed to last for 20 years. However, except for the top layers, most roads have a lifespan of 40–60 years (Norwegian Public Roads Administration 2016).

Research Question 3 was approached using the Norwegian software SteinLCA (aggregatesLCA) and VegLCA (roadLCA) developed to match Norwegian conditions specifically, from the production of material through transportation and construction to the end of life. SteinLCA and VegLCA were developed by Multiconsult AS and Asplan Viak AS, respectively. The emission factors reflect the current emissions reported in environmental product declarations (EPDs) representative of the relevant sectors in Norway (Hov *et al* 2019, Andvik *et al* 2021).

Altogether, the research questions covered possible scenarios of adaptation and the effect of climate change on emissions in road construction. Addressing these research questions provided insight into how future climate conditions and life-cycle emissions can be included in the design criteria of frost protection layers.

2. Method

The case study was based on two Norwegian highway sections: E6 Kolomoen–Moelv and E18 Tvedestrand–Arendal. The projects were selected based on location, time of construction, and road design. E6 Kolomoen–Moelv is located inland, in south-east Norway, with frost quantities reaching the maximum design depths of Norwegian road construction. E18 Tvedestrand–Arendal is located in south Norway along the coastline, with frost quantities in the lower range on the Norwegian scale. Figure 2 presents the road sections and the frost quantities in Norway.

Both road sections are new four-lane highways with geometric design criteria of the cross-section, as presented in figure 3. The design criteria for public roads in Norway are given by the Handbook N100 Road and Street Design (Norwegian Public Roads Administration 2021b) and Handbook N200 Road Construction (Norwegian Public Roads Administration 2021c).

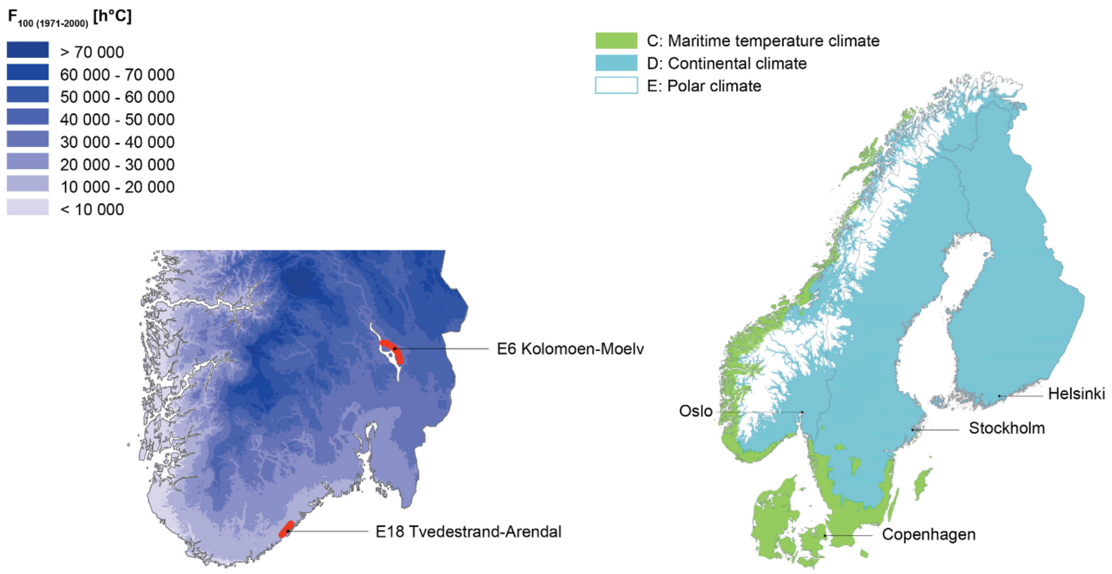

Figure 2. Location of selected road sections, frost quantitates based on 1971–2000 in Norway (left), and climate classification map for Nordic Countries according to the KöppenGeiger system (right).

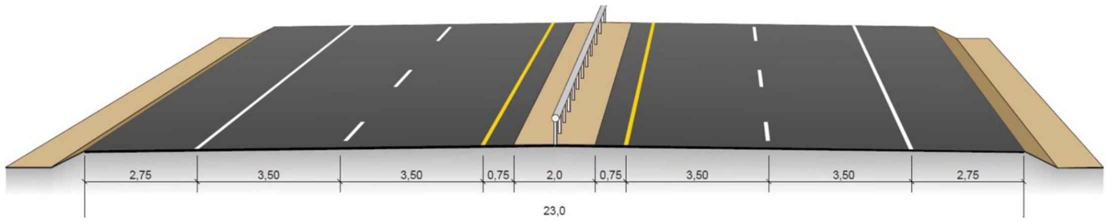

Figure 3. Cross-section of H3 National main road, AADT $>$ 12 000, speed limit $=$ 110 km h^{-1} (Norwegian Public Roads Administration 2021b). Reproduced with permission from Norweigian Public Roads Administration.

The pavement design with Norwegian requirements and regulations in 2022 was compared with that in 2071–2100, based on the assumption that only the frost quantity changes in the pavement design. However, thin frost protection layers change the structural design in some scenarios owing to bearing capacity requirements.

The frost quantities in 2071–2100 were based on scenarios RCP4.5 and RCP8.5, presented in IPCC's fifth assessment report (IPCC 2014, Hanssen-Bauer *et al* 2017).

2.1. Pavement design in 2022 based on the statistical period 1981–2010

The road structure design criterion of the four-lane road stretches is F_{100}, provided by an interactive map published and operated by the NPRA (Norwegian Public Roads Administration 2021a). $F_{100\_1981\text{-}2010}$ is based on local weather statistics for the period 1981–2010 with the possibility of selecting data for a specific project location with a grid of 1 km. The frost depth was calculated based on tables and figures presented in Chapter 521 in the Norwegian pavement design guide (Norwegian Public Roads Administration 2021c) and adjusted using the mean annual temperature provided by an interactive map published and operated by the NPRA (Norwegian Public Roads Administration 2021e).

2.2. Pavement design in 2071–2100

The frost design of 2071–2100 was based on the projections by the NCCS with the scenarios RCP4.5 and RCP8.5. The dataset of F_{100} for 1971–2000 ($F_{100\_1971\text{-}2000}$) and 2071–2100 ($F_{100\_2071\text{-}2100}$) provides one value from each municipality in Norway. The decrease in F_{100} in specific project areas was assumed to be at the same rate as that in the municipality centre. The design in 2022 was based on F_{100} for 1981–2010 ($F_{100\_1981\text{-}2010}$). $F_{100\_2071\text{-}2100}$ in the specific project area was based on $F_{100\_1981\text{-}2010}$ multiplied by the ratio of $F_{100\_1971\text{-}2000}$ to $F_{100\_2071\text{-}2100}$ at the municipality centre. The input data for pavement design for 2022 and 2071–2100 are presented in table 1.

Table 1. Design data pavement design of E6 Kolomoen–Moelv and E18 Tvedestrand–Arendal.

	E6 K–M	E18 T–A
Design period	20 years	20 years
Number of lanes	4	4
AADT (annual average daily traffic)	12 500 (2019)	13 550 (2018)
Share long vehicles	18%	17%
ESALS (equivalent 10 tonne axels)	9200 000	9420 000
$F_{100\_1971\text{-}2000}$ (municipality centre)	37 300 h °C	14 800 h °C
$F_{100\_1981\text{-}2010}$ (project location)	40 350 h °C	13 000 h °C
$F_{100\_2071\text{-}2100}$ RCP4.5 (project location)	24 100 h °C	5000 h °C
$F_{100\_2071\text{-}2100}$ RCP8.5 (project location)	19 600 h °C	2650 h °C
Average annual temperature	4 °C	7 °C
Average annual temperature RCP4.5	6.7 °C	9.4 °C
Average annual temperature RCP8.5	8.5 °C	10.8 °C
Frost depth 2022	2.68 m[a]	1.40 m
Frost depth 2071–2100 RCP4.5 (% of 2022)	1.91 m (71%)	1.06 m (75%)
Frost depth 2071–2100 RCP8.5 (% of 2022)	1.65 m (62%)	0.69 m (49%)
Wearing, binder and base course	Asphalt concrete	
Subbase material	Crushed rock, open graded, drained, 1% water content (weight)	
Frost protection material	Crushed rock, well graded, slightly frost susceptible, not drained, 8% water content (weight), T2[b]	
Natural subgrade	Gravel, sand, moraine, T3[b]	

[a] Limited by the maximum pavement design depth of 2.4 m for four-lane roads and AADT > 8000 according to Norwegian road design requirements.
[b] Frost susceptibility class in Norwegian road design, see figure 4.

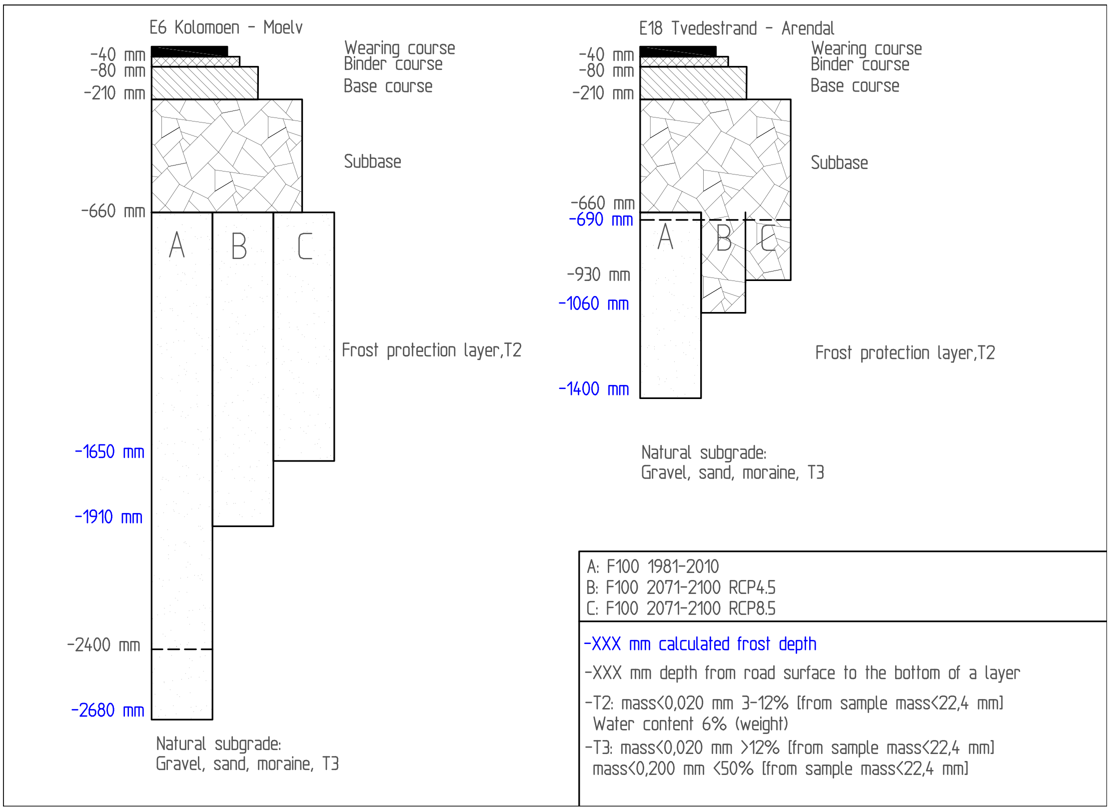

Figure 4. Pavement design of E6 Kolomoen–Moelv and E18 Tvedestrand–Arendal based on N200 Road construction. A: $F_{100\_1981\text{-}2010}$, B: $F_{100\_2071\text{-}2100}$ RCP4.5, and C: $F_{100\_2071\text{-}2100}$ RCP8.5.

The traffic data was provided by an interactive map accessing the National Road Data Bank (Norwegian Public Roads Administration 2021d) and analysed with projections to estimate the AADT and share of heavy vehicles in the opening year. The design criteria of each layer are provided in the empirical based pavement design guide N200 Road Construction; the pavement designs of E6 Kolomoen–Moelv and E18 Tvedestrand–Arendal are presented in figure 4.

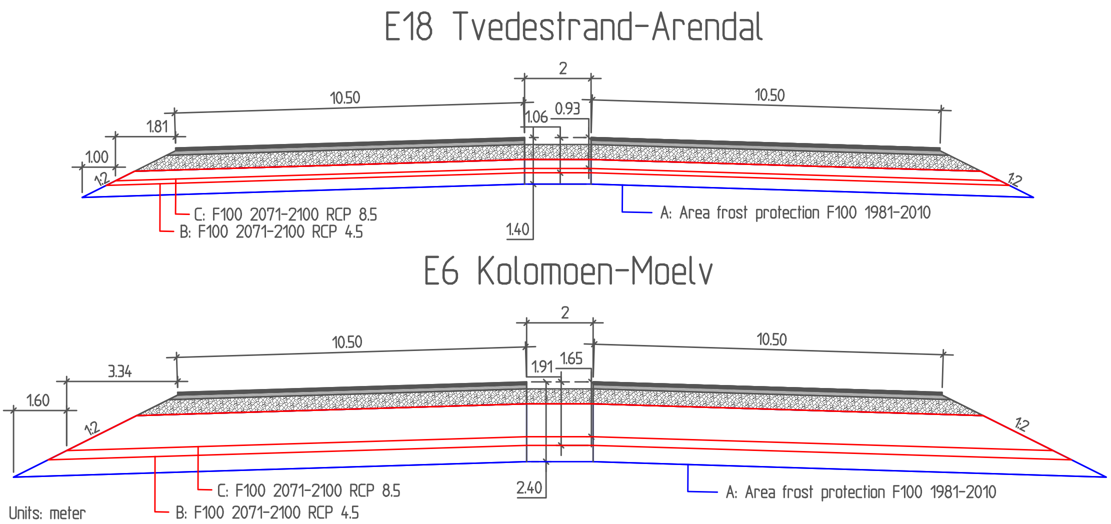

Figure 5. Cross section design of E18 Tvedestrand–Arendal and E6 Kolomoen–Moelv based on N200 Road construction. A: $F_{100\_1981\text{-}2010}$, B: $F_{100\_2071\text{-}2100}$ RCP4.5, and C: $F_{100\_2071\text{-}2100}$ RCP8.5.

The area of the frost protection material in the road section can be calculated based on the geometry of the cross-section and pavement design (figure 5). In the comparison of pavement design in 2022 and 2071–2100 of E6 Kolomoen–Moelv, the only variables are the frost depth and the corresponding area of the frost protection material.

The pavement design of E18 Tvedestrand–Arendal in 2071–2100 had two variables because the calculated frost depths were too shallow to include a frost-protection layer. Thus, the thickness of the subbase layer was increased to replace the thin frost-protection layer. With $F_{100\_2071\text{-}2100}$ RCP4.5, the subbase layer thickness was calculated based on the frost depth. With $F_{100\_2071\text{-}2100}$ RCP8.5, the subbase layer thickness was based on a minimum requirement related to the bearing capacity. The difference in the amount of frost protection and subbase material can be calculated into the reduced material production, transportation, and construction. Furthermore, for each step (blasting, crushing, screening, loading, transportation, and construction), the corresponding kg CO_2-equivalent can be calculated.

2.3. Calculation of kg CO_2-equivalent in a Norwegian context

In the life-cycle assessment (LCA) of road construction in Norway, SteinLCA can be used to calculate GHG emissions from aggregate production and transport (Hov *et al* 2019), and VegLCA can be applied to calculate GHG emissions from in situ activities of road construction (Hammervold 2020).

2.3.1. Emission factors and assumptions

The calculations in SteinLCA v1.0 were based on state-of-the-art technology in Norway 2019 (Hov *et al* 2019), with minor updates in September 2020. Emission factors in VegLCA v5.05B assume 'Nordic electricity mix' in the production of materials in Norway, and EXIOBASE v3 was used to provide emission factors dependent on the sector (construction or transportation) (Andvik *et al* 2021). In the calculations, one crushing stage was assumed for the production of the frost protection and subbase material. Using SteinLCA, the GHG emissions from crushing stage 1 were calculated with the average values of steps 1–4 in figure 6 (blasting to storage/silo) based on the EPDs of Feiring Bruk AS (Feiring Bruk AS 2018a, 2018b, Hov *et al* 2019).

The CO_2-equivalent of every process in the calculations are listed in table 2, which represent the standard values in SteinLCA v1.0 and VegLCA v5.05B (Hov *et al* 2019, Andvik *et al* 2021). CO_2-equivalents of transportation by electric trucks were based on well-to-wheels (WTWs) estimates covering GHG and criteria air pollutant emissions associated with the upstream generation of electricity and loss in transmission and distribution of forces. The estimate was based on comparison with the fossil-fuel consumption of a Euro 6 16–32 t truck of 0.04 l/tkm (SteinLCA) with efficiencies of 34% (diesel) and 85% (electric trucks) and a Nordic electricity mix of 0.047 kg CO_2-eq./kWh (VegLCA). Large variations have been reported in emissions from the maintenance and wear of electric trucks (Earl *et al* 2018) and this is assumed to be the same for electric, biofueled, and Euro 6 16–32 t trucks. Machinery utilised in the levelling of masses and compaction was assumed to have an efficiency of 34% for fossil-fuelled engines and 85% for electric engines.

Figure 6. Steps included in crushing plant stage 1 (Feiring Bruk 2018a). Reproduced with permission from Feiring Bruk AS.

Table 2. Kg CO_2-equivalent of units and processes in SteinLCA[1] and VegLCA[2].

Type	Unit	kg CO_2-eq.
Electricity	kWh	0.047[2]
Electricity	MJ	0.013[2]
Diesel	l	3.240[2]
Biodiesel	l	1.920[2]
Crushing plant stage 1	tonne	2.200[1]
Loading digger fossil fuel	m^3	0.518[1+2]
Loading digger (except fuel)	m^3	0.055[1]
Loading digger electric	m^3	0.019[1+2]
Electric truck WTW	tkm	0.008[2]
Euro 6 16–32 t truck (fossil fuel)	tkm	0.130[1+2]
Biofueled 28 t truck	tkm	0.115[1+2]
Euro 6 16–32 t/ Electric/Biofueled 28 t truck (except fuel)	tkm	0.022[1]
Levelling of masses in construction (fossil fuel)	m^3	3.564[1+2]
Compaction of masses (fossil fuel)	m^2	0.032[2]
Levelling of masses in construction (electric)	m^3	0.221[1+2]
Compaction of masses (electric)	m^3	0.004[2]

Units of tonne/m^3 of blasted rock were applied to calculate volumes and mass in production, loading, transportation, and compacted frost protection layer in road construction. Based on average specific densities of Norwegian rock types listed in NS 3420-F, table B.1 (NS 3420-F:2019 2019), 2.9 t m^{-3} was the assumed density for bed rock before blasting with factors of 1.6 and 1.4 applied for uncompacted and compacted materials, respectively (NS 3420-F:2019 2019). This implies 1.8 t m^{-3} in transportation, loading, and storage, which is in accordance with the findings in the pre-phase of implementing EFFEKT (Hammervold 2009), which is a Norwegian analytical tool implemented by the NPRA to estimate the costs and benefits of road construction, and both SteinLCA and VegLCA are based on this tool (Hov *et al* 2019, Hammervold and Sandstrand-Dahlstrøm 2020).

The compaction of masses was assumed in layers of 50 cm depth in estimates of kg CO_2-equivalents. A layer at a depth of 50 cm is at the maximum depth in the compaction of unbound layers according to the NPRA requirements. However, on the subgrade of clay with a shear strength (cu) <50 kPa, the layer thickness is increased to avoid ground failure. To simplify the calculations, the average value of the kg CO_2-eq./m^3 was applied in the general equations for frost depths between 0.51 and 2.4 m. Table 3 presents the factors and units used in the calculations.

Depending on the bedrock quality and mass balance of the road construction project, blasted rock originating from cutting in the alignment may be processed using on-site mobile crushers and used in road construction (Norwegian Public Roads Administration 2021c). However, the bedrock quality should be sufficient with respect to, e.g. fragmentation, abrasion, and flakiness (Norwegian Public Roads Administration 2021c). These quality parameters, together with the production of fines, depend on geology and production techniques (Fladvad and Onnela 2020), and statistics indicate a low share of utilised materials to be produced on-site (Rise *et al* 2019). There are no mechanical requirements for materials used in frost protection. However, there are requirements related to the share of fines to ensure that the frost protection material is not frost-susceptible. In many scenarios, blasted and crushed rock materials from the alignment require screening to satisfy the fines content requirements. In these scenarios, a frost protection material must be obtained from a stationary crushing plant or transported, screened, and stored on-site, which also generates GHG emissions. Thus, the calculations were based on aggregate production from a stationary crushing plant, with no use of material produced on-site.

Table 3. Factors and units in the calculations with sources.

Type	Amount	Unit	Source
Energy in diesel	10.70	kWh l^{-1}	VegLCA v5.5B (Andvik *et al* 2021)
Efficiency diesel engine	34	%	VegLCA v5.5B (Andvik *et al* 2021)
Efficiency electric engine	85	%	VegLCA v5.5B (Andvik *et al* 2021)
Euro 6 16–32 t truck fossil fuel	0.04	l/tkm	VegLCA v5.5B (Andvik *et al* 2021)
Biofueled 28 t truck	0.06	l/tkm	VegLCA v5.5B (Andvik *et al* 2021)
Levelling of masses fossil fuel	1.10	l m^{-3}	VegLCA v5.5B (Andvik *et al* 2021)
Compaction of masses fossil fuel	0.02	l m^{-2}	VegLCA v5.5B (Andvik *et al* 2021)
Specific density rock (average)	2.90	t m^{-3}	NS 3420-F, table B.1 (NS 3420-F:2019 2019)
Mass factor bedrock	1.00	m^3 m^{-3}	NS 3420-F, table B.3 (NS 3420-F:2019 2019)
Mass factor uncompacted	1.60	m^3 m^{-3}	NS 3420-F, table B.3 (NS 3420-F:2019 2019)
Mass factor compacted	1.40	m^3 m^{-3}	NS 3420-F, table B.3 (NS 3420-F:2019 2019)

Table 4. Alternative 1: kg CO_2-equivalent/m^3 values of frost protection material in processes independent of transport distance.

	m^3	kg CO_2-eq
Crushing plant stage 1	1	4.557
Loading digger fossil fuel	1	0.592
Loading digger (except fuel)	1	0.063
Levelling of masses in construction fossil fuel	1	3.564
Compaction of masses in construction fossil fuel	1	0.065
Total emissions independent of transport	1	8.841

2.3.2. Alternatives in calculating kg CO_2-equivalents

To calculate kg CO_2-equivalents, three alternatives are presented:

(1) An alternative based on fossil-fuelled machinery used in loading, construction, and transportation in 2022 and 2071–2100.
(2) An alternative based on electric machinery used in loading and construction and biofueled trucks in transportation in 2022 and 2071–2100.
(3) An alternative based on fossil-fuelled machinery used in loading, construction, and transportation in 2022, and electric machinery used in loading, construction, and transportation in 2071–2100.

Alternative 1 and 2 was designed based on the assumption that nothing but the frost quantity changed. All design requirements (e.g. bearing capacity, material parameters and lane width) are equal in the pavement design of 2022 and 2071–2100. The alternatives were designed based on relevant machinery available on the market and machinery in use in Norwegian road construction in 2022 (Wiik *et al* 2020). Most machinery used in loading, construction and transportation related to Norwegian road construction are fossil-fuelled. However, biofueled trucks and electric machinery used in loading and construction are available and in use, especially in urban construction sites. Alternative 3 was designed to consider both the change in frost quantity and the Norwegian national goals of zero-emission vehicles and machinery (Ministry of Transport 2020).

The equations of kg CO_2-equivalents for different alternatives are presented with the volume (m^3) of the frost protection material and transportation distance as variables. The calculated volume of the frost protection layer in the constructed road is for the compacted material. However, the emissions presented in table 2 are related to the loading and transportation of the uncompacted masses. Thus, the emission factors presented in the following alternatives were adjusted using the mass factors listed in table 3.

2.3.2.1. Alternative 1: fossil-fuelled machinery 2022 and 2071–2100

The kg CO_2-equivalent/m^3 values independent of transportation distance are presented in table 4. In addition, the transportation of masses in kg CO_2-equivalent/(m^3·km) was calculated and is presented in table 5. Together, they are presented in equation (1), which was used in the calculations of alternative 1,

$$\text{kg CO}_2 - \text{eq.}/\text{m}^3 = 8.841 + 0.314 * \text{transport distance (km)} \quad (1)$$

Table 5. Alternative 1: kg CO_2-equivalent/m^3 of frost protection material dependent of transport distance.

	m^3·km	kg CO_2-eq
Euro 6 16–32 t truck (except fuel)	1	0.046
Euro 6 16–32 t truck fossil fuel	1	0.268
Total emissions transport	1	0.314

Table 6. Alternative 2/alternative 3: kg CO_2-equivalent/m^3 of frost protection material in processes independent of transport distance.

	m^3	kg CO_2-eq
Crushing plant stage 1	1	4.557
Loading digger electric	1	0.021
Loading digger (except fuel)	1	0.063
Levelling of masses in construction electric	1	0.221
Compaction of masses in construction electric	1	0.008
Total emissions independent of transport	1	4.871

Table 7. Alternative 2: kg CO_2-equivalent/m^3 of frost protection material dependent of transport distance.

	m^3·km	kg CO_2-eq
Biofueled 28 t truck (except fuel)	1	0.046
Biofueled 28 t truck	1	0.239
Total emissions transport	1	0.284

Table 8. Alternative 3: kg CO_2-equivalent/m^3 of frost protection material dependent of transport distance 2071–2100.

	m^3·km	kg CO_2-eq
Electric truck WTW (except fuel)	1	0.046
Electric truck WTW	1	0.017
Total emissions transport	1	0.062

2.3.2.2. Alternative 2: electric machinery in loading and construction, biofueled trucks in transportation 2022 and 2071–2100

The kg CO_2-equivalent/m^3 values independent of transportation distance are presented in table 6. In addition, the transportation of masses in kg CO_2-equivalent/(m^3·km) was calculated and is presented in table 7. Together, they are presented in equation (2), which was used in the calculations of alternative 2,

$$\text{kg CO}_2 - \text{eq/m}^3 = 4.871 + 0.284 * \text{transport distance (km)} \quad (2)$$

2.3.2.3. Alternative 3: fossil-fuelled machinery used in loading, construction, and transportation in 2022 and electric machinery in 2071–2100

The kg CO_2-equivalent/m^3 values calculated in 2022 were the same as those in equation (1). For the kg CO_2-equivalent/m^3 values calculated for 2071–2100, we assumed electric machinery in loading, construction, and transportation, as presented in tables 6, 8, and equation (3),

$$\text{kg CO}_2 - \text{eq/m}^3 = 4.871 + 0.062 * \text{transport distance (km)} \quad (3)$$

3. Results

3.1. Estimations of frost index F_{100} based on the statistical period 2071–2100

The projections by NCCS were based on scenarios RCP4.5 and RCP8.5, with calculations of the statistical frost quantity F_{100} of all Norwegian municipalities (357). The reduction in $F_{100\_2071\text{-}2100}$ relative to $F_{100\_1971\text{-}2000}$ for scenarios RCP4.5 and RCP8.5 ranged between 33%–84% and 48%–97% (figure 7). The municipalities with minor $F_{100\_1971\text{-}2000}$ had the highest relative reduction in $F_{100\_2071\text{-}2100}$. The areas with $F_{100\_1971\text{-}2000} < 30\,000$ h °C had an average reduction in F_{100} of 59% under RCP4.5 and a 75% reduction

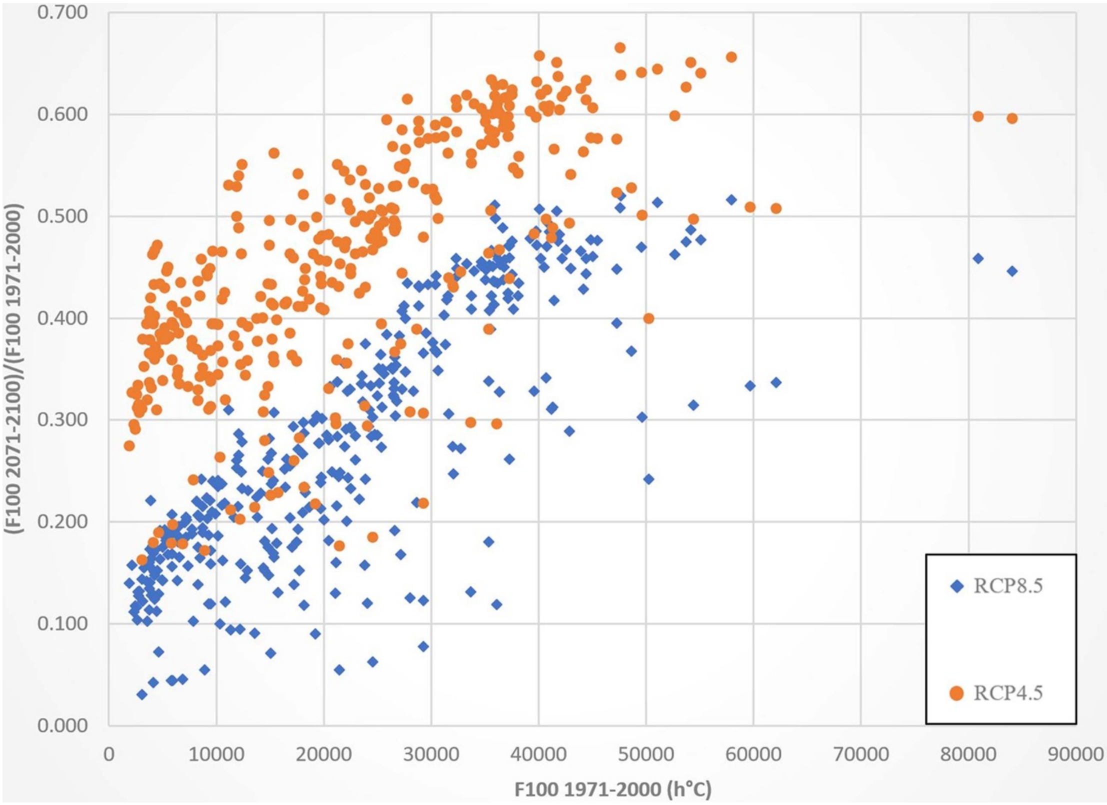

Figure 7. Frost quantity F100_2071–2100 relative to F100_1971–2000 based on RCP4.5 and RCP8.5, all Norwegian municipalities.

under RCP8.5. The areas with $F_{100\_1971\text{-}2000} > 30\,000$ h °C had an average reduction of 43% and 58% under RCP.4.5 and RCP8.5, respectively.

3.2. Estimations of frost protection volumes and kg CO_2-equivalents

The estimations of CO_2-equivalents were based on the frost index $F_{100\_1981\text{-}2010}$ (current design criteria) and estimated $F_{100\_2071\text{-}2100}$ under the scenarios RCP4.5 and RCP8.5. In addition to the current $F_{100\_1981\text{-}2010}$ and scenarios of $F_{100\_2071\text{-}2100}$, three alternative calculations of kg CO_2-equivalents were obtained based on different power sources, as presented in section 2.3.2.

In all calculations, 17.4 km was assumed as the average transportation distance. This was in accordance with the average transport distance of aggregates from production to customers in Norway in 2019 (Norwegian Directorate of Mining 2020).

3.2.1. Alternative 1: fossil-fuelled machinery 2022 and 2071–2100

This alternative was calculated using equation (1). Based on Norwegian road design criteria, the volume of frost protection material per metre of road was calculated using $F_{100\_1981\text{-}2010}$, $F_{100\_2071\text{-}2100}$ RCP4.5 and $F_{100\_2071\text{-}2100}$ RCP8.5. Based on the estimates of the two scenarios, the reduction in kg CO_2-equivalents owing to adaptation was calculated using $F_{100\_1981\text{-}2010}$ as a reference (table 9).

The E6 Kolomoen–Moelv is a 40 km stretch. With $F_{100\_1981\text{-}2010}$ as the design criteria, this corresponds to a total of 29 017 t of CO_2-equivalents produced in the material production, loading, transportation, and construction of the frost protection layer. Under RCP4.5 and RCP8.5 the estimated reductions for $F_{100\_2071\text{-}2100}$ were 30.7% and 46.2%, respectively (table 10). If there were no restrictions on maximum pavement design depth, the reductions would be 41.6% and 54.7%, respectively.

E18 Tvedestrand–Arendal is a 22 km stretch. With $F_{100\_1981\text{-}2010}$ as the design criteria, this corresponds to a total of 6298 t CO_2-equivalents produced in the material production, loading, transportation, and construction of the frost protection layer. Under RCP4.5 and RCP8.5, the estimated reductions with design criteria $F_{100\_2071\text{-}2100}$ were 47.4% and 64.9%, respectively (table 10). However, there is no frost protection layer in any of the 2071–2100 scenarios. Under RCP8.5, the subbase must be increased by 27 cm to fulfil the criteria related to the bearing capacity (owing to a thin theoretical frost protection layer). This corresponds to a total thickness of 93 cm for the pavement design, whereas the calculated frost penetration was 69 cm. Thus, a further reduction in frost quantity would not further reduce the material used in the construction.

Table 9. Alternative 1. Estimated kg CO_2-equivalents related to change in frost protection layer per metre of road.

Units/metre of road		$F_{100\_1981\text{-}2010}$	$F_{100\_2071\text{-}2100}$ RCP4.5	$F_{100\_2071\text{-}2100}$ RCP8.5
E6 Kolomoen–Moelv	Design depth (m), maximum 2.4 m	2.40 (2.68)	1.91	1.65
	Volume (m^3)	50.71	35.14	27.26
	kg CO_2-equivalents production, loading, construction	448.34	310.68	241.01
	kg CO_2-equivalents transport	277.08	192.01	148.95
	kg CO_2-equivalents total	725.42	502.69	389.96
	kg CO_2-equivalents reduction	—	222.73	335.46
	% Estimated reduction CO_2-eq.	—	30.7%	46.2%
	(Not considering maximum 2.4 m)	—	(41.6%)	(54.7%)
E18 Tvedestrand–Arendal	Design depth (m)	1.40	1.06	0.93
	Volume (m^3)	20.01	10.52[a]	7.03[a]
	kg CO_2-equivalents production, loading, construction	176.91	93.01	62.15
	kg CO_2-equivalents transport	109.34	57.48	38.41
	kg CO_2-equivalents total	286.25	150.49	100.57
	kg CO_2-equivalents reduction	—	135.76	185.68
	% Estimated reduction CO_2-eq.	—	47.4%	64.9%

[a] Net change in frost protection and subbase volume.

Table 10. Alternative 1. Estimated total tonne of CO_2-equivalents of material production, loading, transportation, and construction related to frost protection layer of E6 Kolomoen–Moelv and E18 Tvedestrand–Arendal (40 and 22 km).

		$F_{100\_1981\text{-}2010}$	$F_{100\_2071\text{-}2100}$ RCP4.5	$F_{100\_2071\text{-}2100}$ RCP8.5
E6 K–M (40 km)	Tonne CO_2-equivalents, total	29 017	20 108	15 599
	Tonne CO_2-equivalents, reduction	—	8909	13 418
	Tonne CO_2-eq. reduction per metre	—	0.22	0.34
	% Estimated reduction CO_2-eq.	—	30.7%	46.2%
E18 T–A (22 km)	Tonne CO_2-equivalents, total	6298	3311	2212
	Tonne CO_2-equivalents, reduction	—	2987	4085
	Tonne CO_2-eq. reduction per metre	—	0.14	0.19
	% Estimated reduction CO_2-eq.	—	47.4%	64.9%

With RCP4.5, the subbase was further increased by 13 cm to reach the calculated frost penetration depth of 106 cm and fulfil the frost protection design criteria (figure 4).

The estimates of the specific case scenarios matched the overall trend, with a higher reduction in the percentage of frost depth in areas where the frost depth was already relatively low.

3.2.2. Alternative 2: electric machinery in loading and construction, biofueled trucks in transportation 2022 and 2071–2100

This alternative was calculated using equation (2). Based on Norwegian road design criteria, the volume of frost protection material per metre of road was calculated for $F_{100\_1981\text{-}2010}$, $F_{100\_2071\text{-}2100}$ RCP4.5, and $F_{100\_2071\text{-}2100}$ RCP8.5. Based on the estimates of the scenarios, the reduction in kg CO_2-equivalents due to the adaptation was calculated with $F_{100\_1981\text{-}2010}$ as a reference (table 11).

The E6 Kolomoen–Moelv is a 40 km stretch. With $F_{100\_1981\text{-}2010}$ as the design criteria, this corresponds to a total of 19 911 t of CO_2-equivalents produced in the material production, loading, transportation, and construction of the frost protection layer. Compared with alternative 1 with fossil fuels, this was a 31.4% reduction. The change in biofuels amounted to a 9.5% reduction in transportation emissions. In production, loading, and construction, the emissions were reduced by 44.9% in alternative 2 compared with alternative 1.

Under RCP4.5 and RCP8.5 $F_{100\_2071\text{-}2100}$, the estimated tonnes of CO_2-equivalents were reduced at the same rate as alternative 1 because equations (1) and (2) are both linear. The reductions were 30.7% and 46.2% for RCP4.5 and RCP8.5, respectively (table 12). If there were no restrictions on maximum pavement design depth, the reductions would be 41.6% and 54.7%, respectively.

E18 Tvedestrand–Arendal is a 22 km stretch. With $F_{100\_1981\text{-}2010}$ as the design criteria, this corresponds to a total of 4321 t of CO_2-equivalents produced in the material production, loading, transportation, and construction of the frost protection layer.

Table 11. Alternative 2. Estimated kg CO_2-equivalents related to frost protection layer per metre of road.

Units/metre of road		$F_{100\_1981\text{-}2010}$	$F_{100\_2071\text{-}2100}$ RCP4.5	$F_{100\_2071\text{-}2100}$ RCP8.5
E6 Kolomoen–Moelv	Design depth (m), maximum 2.4 m	2.40 (2.68)	1.91	1.65
	Volume (m^3)	50.71	35.14	27.26
	kg CO_2-equivalents production, loading, construction	247.00	171.16	132.78
	kg CO_2-equivalents transport	250.77	173.77	134.80
	kg CO_2-equivalents total	497.76	344.93	267.58
	kg CO_2-equivalents reduction	—	152.83	230.18
	kg CO_2-equivalents reduction	—	30.7%	46.2%
	(Not considering maximum 2.4 m)	—	(41.6%)	(54.7%)
E18 Tvedestrand–Arendal	Design depth (m)	1.40	1.06	0.93
	Volume (m^3)	20.01	10.52[a]	7.03[a]
	kg CO_2-equivalents production, loading, construction	97.46	51.24	34.24
	kg CO_2-equivalents transport	98.95	52.02	34.76
	kg CO_2-equivalents total	196.42	103.26	69.01
	kg CO_2-equivalents reduction	—	93.15	127.41
	kg CO_2-equivalents reduction	—	47.4%	64.9%

[a] Net change in frost protection and subbase volume.

Table 12. Alternative 2. Estimated total tonne CO_2-equivalents of material production, loading, transportation, and construction related to frost protection layer of E6 Kolomoen–Moelv and E18 Tvedestrand–Arendal (40 and 22 km).

		$F_{100\_1981\text{-}2010}$	$F_{100\_2071\text{-}2100}$ RCP4.5	$F_{100\_2071\text{-}2100}$ RCP8.5
E6 K–M (40 km)	Tonne CO_2-equivalents, total	19 911	13 797	10 703
	Tonne CO_2-equivalents, reduction	—	6113	9207
	Tonne CO_2-eq. reduction per metre	—	0.15	0.23
	% Estimated reduction	—	30.7%	46.2%
E18 T–A (22 km)	Tonne CO_2-equivalents, total	4321	2272	1518
	Tonne CO_2-equivalents, reduction	—	2049	2803
	Tonne CO_2-eq. reduction per metre	—	0.09	0.13
	% Estimated reduction	—	47.4%	64.9%

3.2.3. Alternative 3: fossil-fuelled machinery used in loading, construction, and transportation in 2022 and electric machinery used in loading, construction, and transportation in 2071–2100

This alternative was calculated using equations (1) and (3). Based on Norwegian road design criteria, the volume of frost protection material per metre of road was calculated for $F_{100\_1981\text{-}2010}$ and scenarios $F_{100\_2071\text{-}2100}$ RCP4.5 and RCP8.5. Based on the estimates of the scenarios, the reduction in kg CO_2-equivalents due to the adaptation was calculated with $F_{100\_1981\text{-}2010}$ as a reference (table 13).

The E6 Kolomoen–Moelv is a 40 km stretch. With $F_{100\_1981\text{-}2010}$ as the design criteria, this corresponds to a total of 29 017 t of CO_2-equivalents produced in the material production, loading, transportation, and construction of the frost protection layer. The estimated tonnes of CO_2-equivalents with $F_{100\_2071\text{-}2100}$ RCP4.5 and RCP8.5 decreased with respect to both frost depth and change from fossil fuel to electric machinery. The reductions were 71.2% and 77.6% for RCP4.5 and RCP8.5, respectively (table 14). If there were no restrictions on maximum pavement design depth, the reductions would be 75.7% and 81.1%, respectively.

E18 Tvedestrand–Arendal is a 22 km stretch. With $F_{100\_1981\text{-}2010}$ as the design criteria, this corresponds to a total of 6298 t CO_2-equivalents produced in the material production, loading, transportation, and construction of the frost protection layer. The reductions were 78.1% and 85.4% for RCP4.5 and RCP8.5, respectively (table 14).

The alternative includes both changes related to the volume of the frost protection and subbase layer and the shift to electric machinery. The reduction due to the change in the volume of frost protection and subbase material is indicated by alternative 1, where this is the only variating factor. If only the shift to electric machinery is considered, the reduction amounts to 20.5%–58.4% based on equations (1) and (3) and the assumption of an average transport distance of 17.4 km. The estimated reduction in total is presented and ranges from 71.2% to 85.4%.

Table 13. Alternative 3. Estimated kg CO_2-eqiuvalents related to frost protection layer per metre road.

Units/metre of road		$F_{100\_1981\text{-}2010}$	$F_{100\_2071\text{-}2100}$ RCP4.5	$F_{100\_2071\text{-}2100}$ RCP8.5
E6 Kolomoen–Moelv	Design depth (m), maximum 2.4 m	2.40 (2.68)	1.91	1.65
	Volume (m^3)	50.71	35.14	27.26
	kg CO_2-equivalents production, loading, construction	448.34	171.16	132.78
	kg CO_2-equivalents transport	277.08	38.06	29.52
	kg CO_2-equivalents total	725.42	209.22	162.30
	kg CO_2-equivalents reduction	—	516.21	563.12
	kg CO_2-equivalents reduction	—	71.2%	77.6%
	(Not considering maximum 2.4 m)	—	(75.7%)	(81.1%)
E18 Tvedestrand–Arendal	Design depth (m)	1.40	1.06	0.93
	Volume (m^3)	20.01	10.52[a]	7.03[a]
	kg CO_2-equivalents production, loading, construction	176.91	51.24	34.24
	kg CO_2-equivalents transport	109.34	11.39	7.61
	kg CO_2-equivalents total	286.25	62.63	41.85
	kg CO_2-equivalents reduction	—	223.62	244.40
	kg CO_2-equivalents reduction	—	78.1%	85.4%

[a] Net change in frost protection and subbase volume.

Table 14. Alternative 3. Estimated total tonne CO_2-equivalents of material production, loading, transportation, and construction related to frost protection layer of E6 Kolomoen–Moelv and E18 Tvedestrand–Arendal (40 and 22 km).

		$F_{100\_1981\text{-}2010}$	$F_{100\_2071\text{-}2100}$ RCP4.5	$F_{100\_2071\text{-}2100}$ RCP8.5
E6 K–M (40 km)	Tonne CO_2-equivalents, total	29 017	8369	6492
	Tonne CO_2-equivalents, reduction	—	20 648	22 525
	Tonne CO_2-eq. reduction per metre	—	0.52	0.56
	% Estimated reduction in total	—	71.2%	77.6%
	% Reduction due to design depth	—	30.7%	46.2%
	% Reduction with equation (3) compared with equation (1)	58.4%	40.5%	31.4%
E18 T–A (22 km)	Tonne CO_2-equivalents, total	6298	1378	921
	Tonne CO_2-equivalents, reduction	—	4920	5377
	Tonne CO_2-eq. reduction per metre	—	0.22	0.24
	% Estimated reduction in total	—	78.1%	85.4%
	% Reduction due to design depth	—	47.4%	64.9%
	% Reduction with equation (3) compared with equation (1)	58.4%	30.7%	20.5%

Table 15. Electricity mixes in the sensitivity analysis of alternative 3.

Type	kg CO_2-eq./kWh	Source
Nordic electricity mix in VegLCA v5.5B	0.047	(Andvik *et al* 2021)
Norwegian electricity mix 2015–2075	0.018	(NS-EN 3720:2018)
European average 2015–2075	0.136	(NS-EN 3720:2018 2018)
EU average 2019	0.334	(Scarlat *et al* 2022)

The carbon emission associated with the production of electricity was a variable in the calculations, and a sensitivity analysis was performed to describe the influence of choice of relevant electricity mixes listed in table 15 on the results.

Using equation (3), the contribution of electric power usage with the Nordic electricity mix in machinery was 0.251 kg CO_2-eq./m^3 (5.1%), with all processes independent of transport and 0.017 kg CO_2-eq./(m^3·km) (26.8%) of emissions related to transport.

Based on alternative 3 coupled with electricity mixes presented in table 15, the calculations of total tonne CO_2-equivalents of E6 Kolomoen–Moelv (40 km) and E18 Tvedestrand–Arendal (22 km) are presented in table 16. Furthermore, the relative reduction in tonne CO_2-equivalents is presented with $F_{100\_1981\text{-}2010}$ and

Table 16. Alternative 3. Sensitivity analysis calculations of CO_2-equivalents E6 Kolomoen–Moelv (40 km) and E18 Tvedestrand–Arendal (22 km) dependent on electricity mix. Reduction relative to $F_{100\_1981\text{-}2010}$. The estimates based on Nordic electricity mix in VegLCA v5.5B are marked with **bold**.

			Tonne CO_2-eq. in total		Reduction in % CO_2-eq. in total	
	kg CO_2-eq./kWh	$F_{100\_1981\text{-}2010}$	$F_{100\_2071\text{-}2100}$ RCP4.5	$F_{100\_2071\text{-}2100}$ RCP8.5	$F_{100\_2071\text{-}2100}$ RCP4.5	$F_{100\_2071\text{-}2100}$ RCP8.5
E6 K–M	**0.047**	29 017	**8369**	**6492**	**71.2%**	**77.6%**
	0.018		7900	6128	72.8%	78.9%
	0.136		9808	7609	66.2%	73.8%
	0.334		13 011	10 093	55.2%	65.2%
E18 T–A	**0.047**	6298	**1378**	**921**	**78.1%**	**85.4%**
	0.018		1301	869	79.3%	86.2%
	0.136		1615	1079	74.4%	82.9%
	0.334		2142	1432	66.0%	77.3%

equation (1) as references. E6 Kolomoen–Moelv with the $F_{100\_2071\text{-}2100}$ RCP4.5 scenario had the highest sensitivity with a reduction of 55.2%–72.8% depending on the electricity mix.

4. Discussion

The results indicate a considerable decrease in the use of frost protection materials in 2071–2100 based on RCP4.5 and RCP8.5. This reduction was calculated assuming the status quo in every other aspect of road construction. However, from a holistic perspective, the road construction industry and transportation system will undergo development, adaptation, and mitigation that will change the main parameters significantly before 2071. In this chapter, some aspects relevant to the research questions, as well as the possible implications of the results, are addressed.

4.1. RQ1: estimates of frost, geographical, and inter-model variations

The estimated pathways RCP4.5 and RCP8.5 indicate a significant increase in mean annual temperatures throughout the 21st century, and the fifth IPCC-report states that it is 'virtually certain that there will be more hot and fewer cold extremes as global temperature increases' (IPCC 2014). This is consistent with studies of the worldwide 20 year return periods of the lowest annual minimum temperature (Kharin *et al* 2007). However, CMIP3 has been utilised in both studies, and others have emphasised the geographical variations within these models as well as the variations between individual models (Vavrus *et al* 2006, Kodra *et al* 2011). Geographical variations were also observed in studies on Norwegian weather data from 1900 to 2014, where the station Færder (south east) had an average increase in the absolute annual minimum temperature of 0.05 °C per decade during 1900–2014, whereas the corresponding value of Vardø (north east) was 0.17 °C (Førland *et al* 2016). In agreement with these historical data, the general trend in the estimated pathways RCP4.5 and RCP8.5 show a larger relative reduction in areas with minor F_{100} compared with areas with major F_{100}.

Studies also indicate that individual records of cold months (colder than any month in 1901–2000) are likely to occur even towards the end of the 21st century (Räisänen and Ylhäisi 2011). The combination of the increased geographical variation and record cold months because of increased weather extremes indicates that the future frost design of Norwegian roads might exhibit a larger variety in both materials and techniques. This is also in accordance with studies in the US indicating the different impacts of future climate change based on road location (Piryonesi and EL-Diraby 2021).

4.1.1. Uncertainties in future climate estimation

When comparing climate data used in current road design to future scenarios, careful consideration of uncertainties in future model assumptions is important. For this study, three major sources of uncertainty were considered for the future scenarios compared with the status quo: (1) future global CO_2-emission rates, (2) how these emissions influence the global, regional, and local climate, and (3) future changes in energy generation sources. The first and last parameters are dependent on complex socioeconomic models on a global scale, and the second is based on global meteorological models of equal complexity. A comparison of nine dynamically downscaled and bias-corrected global climate models under RCP4.5 in Poland indicated a variation in annual mean temperature in excess of 1.5 °C between the models in 2100 (Mezghani *et al* 2019). Considering that the variation between emission scenarios is larger than that between climate models and that uncertainty levels are higher for more severe scenarios (Shen *et al* 2018), the accumulated uncertainties in future climate modelling are considerable. The sensitivity analysis presented in table 16 shows the influence of emission scenario variation on the calculated total reduction in CO_2 emissions. The relative change in total emissions from RCP4.5 to RCP8.5 is considerably lower than the absolute change in total emissions compared with the base case of the status quo. However, the total emission reduction in future scenarios is not only dependent on future climate change, as the model in alternative 3 assumes the use of electric machinery in 2071–2100. Therefore, the third major source of uncertainty, future changes in energy generation sources, will also have a considerable impact on the results.

4.1.2. Uncertainties in future energy emission factors

The emissions related to the generation of electrical energy are difficult to determine because they relate to the ratios of different energy sources available in a given market, energy flows between markets, and emissions related to each electricity generation plant. Norway is a particularly complex case, as it is connected to the European energy market is also practically self-sufficient in terms of green energy from already established hydropower plants. The Norwegian standard NS 3720 (2018) (NS-EN 3720:2018 2018) provides two alternative energy factors for calculating emissions: one for the Norwegian energy mix and one for the estimated European average mix from 2015 to 2075. The latter is based on the projections presented in the EU Roadmap Towards 2050, with the aim of 90% reduction in GHG emissions by 2050 compared with 2010 (Langsdorf 2011). As shown in the sensitivity analysis presented in table 16, the range of calculated total emissions for the different energy emission factor alternatives is larger than that of the calculated total emissions for the different climate scenario alternatives for both cases. However, it is important to compare these two parameters, i.e. the unchanged energy emission factor contradicts the RCP4.5 scenario. Similarly, it is unlikely that the future energy emission factor will be at the lower extreme combined with a high-extreme emission scenario. Both factors have a significant impact on the results; hence, the uncertainty associated with them should not be neglected. Therefore, the calculation of multiple factor combinations, such as the analysis presented in table 16, is important.

4.2. RQ2: pavement design in 2022 and 2071–2100

The Norwegian design criteria for road construction are based on traffic volume (AADT) and composition of traffic (heavy vehicles, allowed axel load, etc) to optimise the socioeconomic balance between investment costs and service life, maintenance and operations, environmental impact, and traffic safety in all phases (Norwegian Public Roads Administration 2021c). The traffic situation is likely to change owing to the autonomy of vehicles, operation and maintenance equipment, and traffic infrastructure. However, this direction is difficult to predict.

Most countries are at an embryonic stage with regard to nationwide climate adaptation strategies in the transportation sector (Wang *et al* 2020). Additionally, the impacts already posed by climate change underline the demand to implement such strategies (Wang *et al* 2019) and owing to economic implications, the improvement of transportation network resilience has become a high priority in infrastructure planning (Kurth *et al* 2020). However, the current national criteria for pavement design in Norway do not differentiate between geographical locations.

4.2.1. Frost design based on weather data

Even with the possibility of individual months of temperatures lower than registrations of the 20th century (Räisänen and Ylhäisi 2011), the design criterion F_{100} (statistical return period of 100 years) might not be socioeconomically beneficial. Research indicates that compared with the change in average annual temperatures in Norway, the increase in absolute and average annual minimum temperatures is higher (Førland *et al* 2016). This trend implies that shorter return periods of the frost protection criteria might be socioeconomically beneficial in 2071.

The frost projections by NCCS with the scenarios RCP4.5 and RCP8.5 for 2071–2100 estimate F_{50} to be 87% and 89% compared with the F_{100} frost quantity, as an average of all Norwegian municipalities. F_{10} is the current design criterion for roads with less than four lanes. Based on the statistical period 1981–2010 in city centres of all Norwegian municipalities, F_{10} is 58% of the F_{100} frost quantity on average (Norwegian Public Roads Administration 2014). Thus, the volume of frost protection material would be reduced further if the future design criteria are adjusted to F_{10} or F_{50} compared with the estimates based on F_{100}.

Furthermore, the results indicate that there will be few or no highway sections with frost depths of more than 2.4 m based on calculations using F_{100}. Several already constructed highways are designed based on this maximum pavement depth, and the risk of frost penetration into the natural subgrade is more than once in a hundred years, although frost penetration is initially calculated based on F_{100}.

4.2.2. Technical improvements and adaptation to changes in deterioration mechanisms

Fluctuations around 0 °C with consecutive freeze and thaw cycles significantly increase the deterioration of the road structure (Aksnes *et al* 2013, Badeli *et al* 2018, Piryonesi and EL-Diraby 2021). If climate change increases the duration of fluctuations around 0 °C, the pavement design might require changes according to the material properties and composition of the road structure, particularly for low-volume roads.

The development of technology is likely to change the details within or structure of pavements. Research has shown that nanotechnology will improve the durability and reliability of road pavement construction by 2071 (Radziszewski *et al* 2016). We might expect future additives and materials to facilitate the possibility of reducing the frost susceptibility of both road structures and natural subgrades. However, the volumes of the frost protection material and natural subgrade to be processed/substituted are many times the volume of the asphalt layers. In the cross section H3 (see figures 3–5) with bound base course and 2.4 m pavement depth, the unbound layers (which excludes the asphalt layers) represent 94%. Furthermore, the asphalt layers are exposed to higher stresses and strains than the unbound layers (Huang 2004), and the improved properties of these layers might have a better potential to increase the durability of the road structure. Thus, the calculated reduction in material usage in the frost protection layer owing to the estimated reduction in frost depth might be realistic. However, there might be increased costs and material usage related to the production and construction of upper layers in the adaptation to changed climate conditions, but this is outside the scope of this paper.

4.3. RQ3: emissions in 2022 and 2071–2100

Estimates of alternative 3 show possible reductions in emissions related to the material production, loading, transportation, and construction of the frost protection layer ranging from 71% to 85% in 2071–2100. The calculations of energy use and CO_2 equivalents were based on the technology available in 2022. However, vehicle parks, material technology, road construction, and production techniques are likely to undergo significant changes before 2071–2100, with climate change being an interdisciplinary frontier study (Wang *et al* 2020).

4.3.1. Change in environmental consequences trough electrification of machinery

According to the goals of Norwegian National Transportation Plan 2022–2033 (Ministry of Transport 2020), 50% of new trucks should be zero-emission vehicles (hydrogen or electric) by 2030, and construction sites within the transportation industry should be operated without use of fossil fuels by 2025. These national goals are considered in alternative 3, where the reduced volume of the frost protection material is coupled with a shift to electric machinery.

With the use of regenerative braking in electric machinery, there is less wear on brakes, and the drivetrain is simpler e.g. lacking a gearbox (Earl *et al* 2018). Furthermore, it is likely that emissions related to maintenance, operation, and wear will be reduced through technical advancement and electrification of the maintenance equipment. These developments in efficiency, maintenance, operation, and wear were not estimated in the calculations and should amount to further reduction in emissions if they are considered.

However, even with future development, there will be emissions related to maintenance, operation, and wear, and zero-emission cars will still depend on tire-road and brake pad-break disc friction. These non-exhaust emissions have not exhibited a similar trend compared with the reduction in transport-related GHG emissions (Harrison *et al* 2012, Sommer *et al* 2018). Furthermore, electric machinery still depends on the power supply with emissions related to upstream generation.

The estimates of kg CO_2-equivalents related to electric power production differ depending on the power source, with hydropower producing less than 1% kg CO_2-eq./kWh compared with coal production (Woo *et al* 2017). In the sensitivity analysis with relevant electricity mixes, the calculated reduction in kg CO_2-equivalents with alternative 3 differed by 17.6% in the most sensitive combination with E6 Kolomoen–Moelv and scenario RCP4.5. The total reduction in this scenario was 71.2%, whereas the switch to electric machinery represents 40.5%.

The sensitivity analysis only included the electric machinery used in loading, transportation, and construction, as indicated by alternative 3. Electrification in production was not included, which is likely to have a significant contribution. Thus, the results exhibited a significant sensitivity to the emissions associated with upstream power generation, and this dependency will probably be of increased importance in the evaluation of all future energy-consuming operations.

4.3.2. Limitations in calculation of environmental consequences

The impact of climate change on carbon emissions in future road design is continuous, and the period 2023–2071 could also have been included in the study. However, the period 2071–2100 was chosen based on quality of available data.

The production and transportation of materials, construction, maintenance, operation, and end-of-life considerations of roads have a wide spectrum of effects on the environment, including GHG emissions, atmospheric considerations, air pollutant emissions, land use, and abiotic depletion potential of fossil and non-fossil resources.

The case study was limited to calculating GHG emissions related to the production of materials, loading, transport, and construction of the frost protection layer. These limitations reduce the variables and provide the possibility of calculating estimates of reduced GHG emissions within the selected narratives of alternatives and RCP scenarios.

The reduction in land use is one possible quantity that could have been included in the calculation, and the further reduction in GHG emissions would be significant in areas along the vertical alignment with cut volumes (existing terrain is excavated). However, this consideration is specific to each project, and the calculation of these quantities in the selected projects would not reflect real scenarios because the vertical alignment should be adjusted to optimise the mass balance if the pavement design depth is reduced. Therefore, this parameter was not included in the estimates.

4.4. Road construction in 2071–2100 in a national perspective

The entire 810 km of four-lane highways listed in the current National Transport Plan of Norway 2022–2033 will not be built within 2033, and some may never be built. The National Transport Plans for the period 2071–2100 may reduce the number of new roads to be built based on the current road network capacity and share between different modes of transportation. Furthermore, some roads are tunnels, bridges, or built on non-frost susceptible subsoil without thick frost protection layers. Considering these uncertainties, current plans for road construction may not provide a good estimate of four-lane roads to be built with conventional frost protection layer in 2071–2100.

However, if we assume that 400 km of four-lane roads will be built with a conventional frost protection layer in the period 2071–2100, a rough estimate of contributions to the national carbon footprint can be provided. With alternatives 1 and 3 and pathways RCP4.5 and RCP8.5, the estimated reduction in tonne CO_2-equivalents per metre ranges from 0.14–0.56. Assuming the estimated F_{100} in the geographical area of E6 Kolomoen–Moelv and E18 Tvedestrand–Arendal to be representative, this amounts to 56 000–224 000 t CO_2-equivalents with 400 km of road. This corresponds to 0.1%–0.5% of the Norwegian national goal of carbon print reduction from 2019 to 2050 (Norwegian Ministry of Climate and Environment 2021).

Seeing the estimated relative reduction in F_{100} covered in RQ1, it can be argued that statistical return periods based on the past 30 years is too conservative when applied in road design with service life over the next 20–40 years. Furthermore, frost penetration into the natural subgrade once every 100 years might also be considered a too conservative requirement, even for National main roads with AADT $> 12\,000$. However, the choice of climate prediction model also includes a level of accepted risk, and socioeconomic consequences of insufficient frost protection should be considered for each road class. Furthermore, there are barriers related to data curation of pavement design frost quantities covering all of main land Norway and implementation of new regulations, guidelines, and possibly pavement design procedures. Therefore, both the potential switch from statistical return periods based on historical data to future climate predictions, and the level of accepted risk reflected in the choice of statistical return period, should be part of an overall risk assessment covering all road classes. This risk assessment should also cover barriers related to data curation and implementation, which is outside the scope of this paper.

5. Conclusion

Research Question 1 addressed the changes in frost quantities from to 2071–2100 with 1971–2000 as a reference. The RCP4.5 and RCP8.5 pathways exhibited large reductions in the estimated frost quantity $F_{100\_2071\text{-}2100}$ compared with $F_{100\_1971\text{-}2000}$ in all Norwegian municipality centres. Based on RCP4.5, $F_{100\_2071\text{-}2100}$ is decreased by 33%–84% compared with $F_{100\_1971\text{-}2000}$. With RCP8.5, the reduction ranged from 48% to 97%. The reduction in F_{100} was higher in areas that currently have minor frost quantities, and with RCP8.5, the areas with $F_{100\_1971\text{-}2000} < 30\,000$ h °C had an average reduction of 75%.

Research Question 2 was addressed based on the findings related to RQ1. E6 Kolomoen–Moelv and E18 Tvedestrand–Arendal represent areas with major and minor frost quantities within the road network, where the AADT is sufficiently high to consider the construction of four-lane roads in Norway. The case study followed the overall trend with a greater relative reduction in the frost quantity of E18 Tvedestrand–Arendal, which currently has a minor frost quantity compared with E6 Kolomoen–Moelv. The reduction in $F_{100\_2071\text{-}2100}$ with RCP4.5 decreased by 42% and 47% in frost protection layer materials if the maximum road design depth of 2.4 m was not considered. With RCP8.5 and $F_{100\_2071\text{-}2100}$, the estimated reduction of frost protection material was 55% and 65%.

Research Question 3 was approached with three alternative equations to estimate emissions in kg CO_2-equivalents related to the frost protection layer. Alternative 1 with fossil fuel in loading and transport in 2022 and 2071–2100 was limited to estimating the reduced production of tonne CO_2-equivalents based on the assumption that only F_{100} changes. For E18 Tvedestrand–Arendal, the estimates exhibited a 47% reduction with RCP4.5, corresponding to a reduction of 0.14 tonne CO_2-equivalents per metre. With RCP8.5, the estimates exhibited a 65% reduction, corresponding to 0.19 tonne CO_2-equivalents per metre. E6 Kolomoen–Moelv combined with RCP4.5 amounted to a 31% reduction in emissions, corresponding to 0.22 tonne CO_2-equivalents per metre. With RCP8.5, the reduction was estimated at 46%, corresponding to 0.34 tonne CO_2-equivalents per metre.

Alternative 2 covered the difference between biofueled and fossil-fuelled trucks, where the isolated difference in power source amounted to 0.03 kg CO_2-equivalent/(m^3·km) or 10% reduction in transportation emissions. A reduction of 10% is insufficient to achieve the goal of reducing emissions from road traffic by 2050. Closing the gap in existing knowledge to increase volume and reduce emissions in biofuel production is required to satisfy future demands (Gautam *et al* 2020).

Alternative 3 estimated the combined effects of climate change and the shift from fossil fuels to electric machinery and trucks. The estimated reduction in tonne CO_2-equivalents per metre ranged from 0.22–0.56 and 71%–85% with alternative 3 and RCP4.5/RCP8.5, respectively, where the shift to electric machinery represented 21%–41%. Thus, the future development of machinery and road construction has a significant potential to mitigate emissions in the production of materials, loading, transport, and construction. Furthermore, despite combined efforts worldwide to limit global warming, adaptation to climate change has the potential to reduce GHG emissions and costs within the discussed narratives and should be addressed in the regulation of pavement design.

Data availability statement

The data cannot be made publicly available upon publication because they are owned by a third party and the terms of use prevent public distribution. The data that support the findings of this study are available upon reasonable request from the authors.

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